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INTEGRATED AIRCRAFT FUEL TANK FIRE AND EXPLOSION PROTECTION SYSTEMS - PHASE I AND II

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McDonnell Aircraft Company

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INTEGRATED AIRCRAFT FUEL TANK FIRE AND EXPLOSION PROTECTION SYSTEMS - PHASE I AND II

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Aircraft fuel tank fire and explosion protection techniques are described in this two part report which covers both state-of-the-art and advanced concepts. The state-of-the-art section reviews, in handbook form, the fire and explosion protection techniques currently available for immediate aircraft incorporation. These fire protection techniques include open celled flexible foam, closed cell rigid foam, purge mats, and fire extinguishing systems. Both fully packed and voided reticulated foam, nitrogen inerting, fuel fogging, and extinguisher type

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20. explosion suppression systems are discussed under the heading of explosion protection techniques. The advanced explosion protection technique section includes descriptions of on-board nitrogen generating concepts and combination systems of foam/nitrogen/fuel-air fog. In addition, the data and results from a small scale test program evaluating the combination type protection concepts is presented.

NOTICE

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The author wishes to acknowledge other McDonnell Aircraft personnel who made major contributions toward the performance of this effort: E. R. Lake and E. W. Wiggins.

This Technical Report has been reviewed and is approved.

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1.0 INTRODUCTION & SUMMARY

With greater survivability emphasis being given to aircraft design requirements the necessity of data compilation and technique definition in terms of usage applicability to a real environment is required. This data compilation should form the foundation whereby survivability techniques may be employed according to mission requirements and tailored to the aircraft configuration and size to assure effective design. In addition, this data should be presented in a manner usable to designers without specific experience or knowledge in the field of survivability. In an attempt to satisfy this need a two pronged effort was initiated aimed only at aircraft fuel related fire and explosion protection techniques that would: (1) prepare a handbook type document describing fuel system state-of-the-art fire and explosion protection techniques and their applicability to an aircraft environment and (2) present a composite description of advanced fuel tank fire and explosion techniques and conduct a small scale bench type test program to test promising candidate concepts.

Section 2 of this report is a treatise on state-of-the-art fire and explosion protection techniques in handbook form with detailed descriptions of each concept. This handbook is divided into three basic parts. The first part gives a broad brush look at problems and parameters associated with the study of survivable fuel system design and a suggested approach that may be used by the designer in conducting trade studies for his particular requirements. The second and third parts are detailed descriptions of state-of-the-art fire and explosion protection techniques. These descriptions provide the designer with information on the principle of operation, application constraints, system performance, configuration, availability of hardware, benefits, and disadvantages of the various techniques. A system description narrative chart that will provide a brief discussion for each technique is included to give the designer quick review capabilities. The state-of-the-art fire protection techniques for dry bays and other void areas adjacent to the fuel tanks include open cell flexible foam, closed cell rigid foam, purge mats, and fire extinguishing systems. For explosion protection such techniques as fully packed and voided reticulated foam, nitrogen inerting, fuel fogging, and extinguisher suppression are discussed. An evaluation matrix is also presented that will aid the designer as it points out the possible parameters that must be determined to conduct an unbiased trade study for comparison of the applicability of each technique to any particular aircraft design.

Section 3 of this report is intended to describe several advanced fire and explosion protection techniques and present the data derived from testing the most viable and immediate concepts available for aircraft fuel systems. Descriptions of such concepts as on-board nitrogen generating systems by techniques of sorbent bed inert gas generation, catalytic reactor gas generation and permeable membrane inert gas generation are given. Other concepts such as combinations of foam, fuel fog, and nitrogen are also discussed. The later techniques were tested in a small scale apparatus for their inerting or suppression capability. The immediate potential of these systems could be realized in full scale design because of the acceptance of the capability of these systems on an individual basis. It was intended that by combining the most favorable qualities of each of these concepts a protection technique, covering the full range of aircraft mission and environmental requirements, very light weight and minimum fuel volume displacement systems could be developed. The results indicate that a reduction in foam is possible by adding nitrogen to the ullage vapor and for any given allowable tank overpressure, a system designed to use this combination would indeed be lighter weight than either of the two used individually. The use of pneumatically generated fuel fog negated the effects of nitrogen when used in combination and does not appear acceptable from an operational standpoint.

2.0 SURVIVABLE FUEL SYSTEM DESIGN HANDBOOK

2.1 GENERAL

Aircraft fuel systems are designed primarily to provide fuel for power plant operation under all flight environments. Generally, the fuel is contained in a number of tanks from which it is transferred to the engines through the use of boost or ejector pumps. Venting, pressurizing, transferring, refueling, defueling, and level control plumbing complete the system. The fuel system must be designed for survivability, in concert with these primary requirements. The criteria for fuel system survivability is the control or elimination of fuel leakage, fires, and explosions. General system configuration and construction materials play an important part in establishing a survivable aircraft fuel system. A basic rule is to locate tanks such that they are remote from hot components where ignition of any leaking fuel can occur. This can be accomplished by keeping all fuel remote from ignition sources or by providing controlled leakage and drainage paths. The use of integral fuel tanks also can aid in the control of leakage and possible internal airframe fire, since leaking fuel may be dumped directly into the outside air stream, where the high velocity air flow reduces the possibility of ignition and subsequent damaging fire. The use of integral fuel tanks, however, increases the possibility of total fuel loss and possible engine ingestion problems because hydraulic ram coupling of the fuel and structure results in greater tank wall damage. The damage tolerance of this type construction depends upon its ability to withstand the ram pressure generated by the impact. Since structural overpowering of these forces would result in large weight penalties, bladder-cells constructed of fiber-reinforced elastomeric material are used as an alternative. Rip-stop and self-sealing type construction with proper resilient backup withstands the hydraulic ram forces by redistributing them over a larger area due to their elastic deformation, thus minimizing damage and leakage. Figure 1 shows the weight and thickness of such bladders in use.

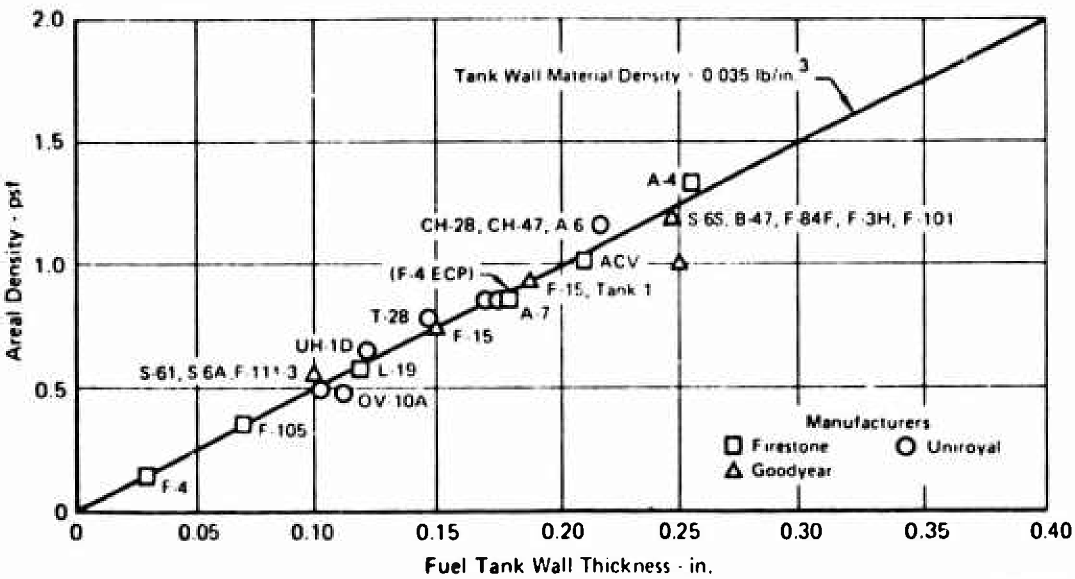

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FIGURE 1
FUEL TANK WALL DENSITY

The expected leakage resulting from various threats versus fuel tank bladder thickness is available in Reference 1. Bladder type tanks are generally off-set from the structure, and the space between the airframe and the tank (dry bays) can become a fire hazard when fuel from damaged or leaking fuel cells drains into these cavities.

Another system detail contributing significantly to aircraft survivability, is the placing of all plumbing in the fuel tanks and as near the top of the tank as possible. Leakage from damaged transfer, vent and engine feed-lines will then occur within the tanks. Further, by placing these lines high in the tank gravity leakage from damaged tank wall fittings is reduced.

Beyond these considerations, further significant survivability improvements can be attained through the use of internal and external fire and explosion protection systems. Parameters for the design and evaluation of state-of-the-art aircraft fire and explosion protection systems are discussed in the following paragraphs.

2.2 FUEL TANK FIRE AND EXPLOSION PROTECTION SYSTEMS

Aircraft fuel tank protection concepts are divided into two general categories; namely fire-protection and explosion-protection systems. Fire protection covers all areas external to the fuel tank and explosion protection addresses the fuel tank ullage. The design of fire protection techniques is more sensitive to environmental considerations than mission requirements. The protection techniques are subject to widely varying environmental parameters including temperature, pressure, and humidity. Further the ignition threat varies from point source sparks to an incendiary or explosive type source, and quite possibly to both of these threats simultaneously, since a projectile could sever electrical cables that may be routed through the void area adjacent to the fuel tanks. Hydraulic lines can be routed through these areas, thus subjecting these protection systems to the possibility of leaking hydraulic fluid and hydraulic fires.

Various techniques for explosion protection have recently been devised and tailored to the aircraft mission requirements. The development of these protection concepts on a mission basis has proven to be very efficient from the standpoint of weight and system effectiveness. Trade studies involving aircraft mission performance parameters and physical configurations must be integrated into the design, in order to keep weight and volume penalties to a minimum.

Typical parameters to be considered in the design of survivable fuel tank protection systems are shown in Figures 2 and 3. These figures represent aircraft fuselage and wing cross-sections, showing the penetration path of a projectile and the design parameters which must be included in protection system trade studies. It is obvious from these figures that the design of fuel tank protection concepts must be an integrated effort, involving both fire and explosion protection techniques in order to develop an overall system.

Definition of many of these design parameters can be fixed once the aircraft mission profile is defined, the numbers specified, and the allowables calculated. Design data generated by using the mission profiles given in Figure 4 can be

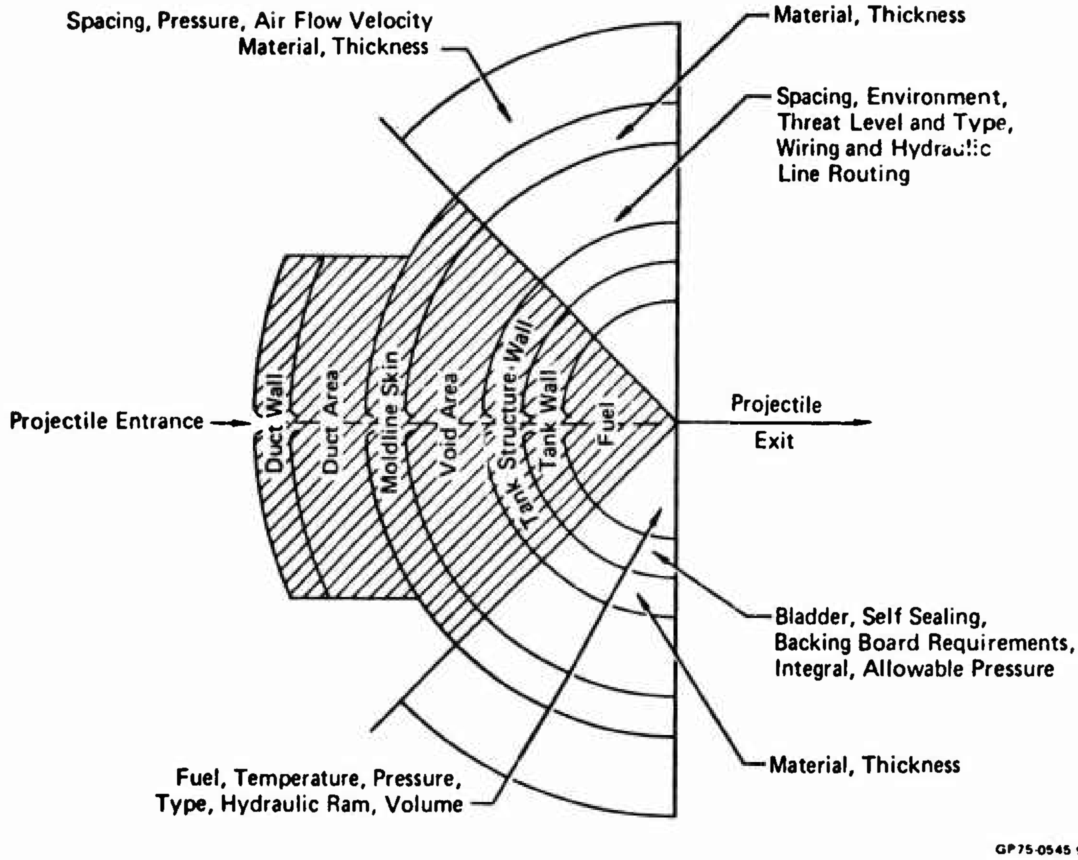

FIGURE 2
FUSELAGE CROSS SECTION (GENERIC)

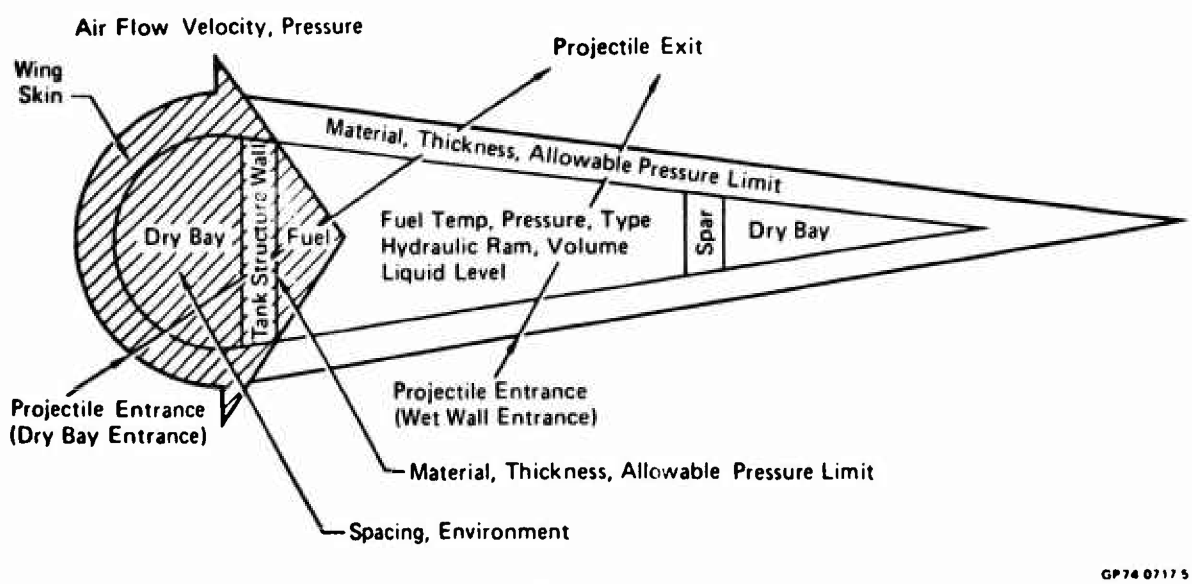

FIGURE 3
WING CROSS SECTION (GENERIC)

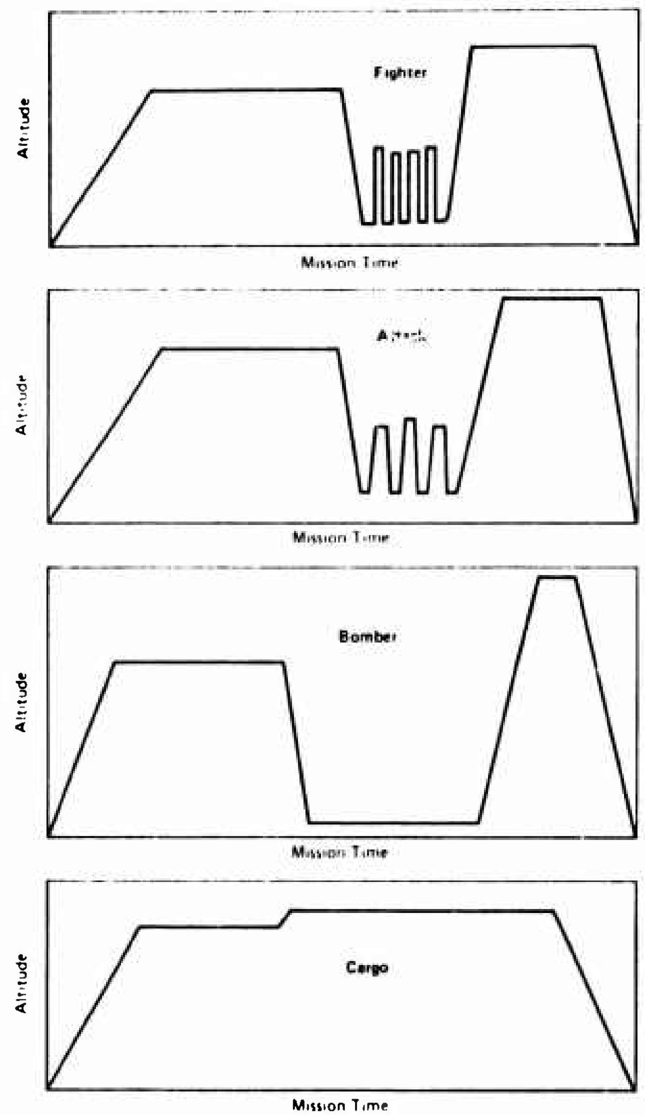

FIGURE 4
AIRCRAFT MISSION PROFILE

transposed to the trade matrix evaluation chart given in Figure 5, for protection system evaluation and design. In addition, a system description narrative (Figure 6) is provided to offer the designer general information describing each state-of-the-art protection concept and its applicability and limitations. These narrative charts for state-of-the-art fire and explosion protection techniques are provided, along with design information, in the following paragraphs.

Aircraft Protection Technique		Weight lb/100 gal Fuel	Fuel Weight Loss lb/100 gal Fuel	System Cost $/100 gal Fuel	Fuel Compatibility	Environmental Compatibility	Fuel Contamination miligrams/gal	Reliability	Logistics
Location	Type								

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FIGURE 5
FUEL TANK FIRE/EXPLOSION TECHNIQUE EVALUATION MATRIX

...on ...d	Reliability	Logistics	Fuel Requirements	Benefits (Threat Environment)					Comments
				Ballistic			Lightning	Spark	
				API	Fragments	HEI			

Principle of
Operation

Application
Constraints
Installation

System
Performance

Configuration

Availability

(This figure shows the probable layout of the system description narrative chart)

Additional
Benefits

Disadvantages

Areas of Concern
or Limitations

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FIGURE 6
SYSTEM DESCRIPTION NARRATIVE CHART

2.3 FIRE PROTECTION TECHNIQUES

An effective means of eliminating airframe fires is the filling of the voids between tanks and walls with a baffling material which eliminates one of the essential fire-sustaining constituents; i.e., airflow, flame propagation, or fuel vapor/mist. The state-of-the-art systems include low-density, open and closed-cell, and/or flexible and rigid foams, in addition to fire extinguishers and inert gas filled purge mats. Material properties and system descriptions follow.

2.3.1 State-Of-The-Art Fire Protection Techniques

2.3.1.1 Open-Cell Flexible Type Foam - Low-density, ether type, reticulated-polyurethane foam used for fire protection systems is similar to the reticulated ester-type polyurethane foam, presently used for explosion protection systems in aircraft fuel tanks. The ether-base material is a more hydrolytically stable compound than the ester-type and lends itself well to the environment of dry bay areas where high temperatures and high humidity are common. This material will swell to some degree when immersed in hydrocarbon-type fuels. The material is presently not covered by a MIL specification; however, its physical properties are presented in Figure 7. The highest cell count (smallest cell size) available to date for this material is 37 pores per inch (ppi), which is more than adequate from a drainage standpoint.

Scott Paper Co's White Polyether Reticulated Urethane Foam

Density (lb/ft^3) 1.35 to 1.45
Pore Size - 30 to 50 (37 nominal) ppi

	Fresh	Aged (1)	Autoclave 5 Hrs (2)	Autoclave 10 Hrs (3)
Tensile (PSI)	24.0	18.0	19.0	18.0
Elongation (%)	275	260	300	300
Tear (lb/in)	5.0	5.0	4.5	-
Compression load deflection				
at 25 percent deflection (PSI)	0.30	0.25	0.25	-
65 percent deflection (PSI)	0.53	0.37	0.37	-
Compression Set				
50%	10%	-	-	-
90%	15%	-	-	-
Fluid Retention	Sunoco 190		8.5%	
(per Mil-B-83054)	Diesel Fuel		14.0%	
Fuel Swell Data - % Volume Swell - 7 Day Immersion				
Sun Gas - 190	30-35%			
Sun Gas - 260	40-45%			
JP-5	19-22%			

Footnotes: (1) 22 hrs. @ 140°C
(2) 5 hrs. @ 15 psi steam
(3) 10 hrs. @ 15 psi steam

Data Supplied by Scott Paper Co.

FIGURE 7
PHYSICAL PROPERTIES AND CHARACTERISTICS

SYSTEM DESCRIPTION NARRATIVE CHART - OPEN CELLED FLEXIBLE FOAM

Principle of Operation	Reduces spray of fuel from leaking tanks and lines and physically inhibits mixing of fuel and air needed for sustained fires. The foam is open-cell, permitting free drainage of leaking fuel to drain holes located at low points in the aircraft.
Application Constraints	Install under 3 to 5% compression. Design and cut foam to fit the contour of the bay. Cut-outs are not required for small equipment and plumbing. The material is simply draped over lines and equipment located in the dry bay areas and compressed to fit into the required area. Cutting techniques, acceptance tests, and procedures are identical to those for the polyester type explosion protection foam described in Section 4.
System Performance	In most installations, this material provides excellent fire protection up through 23 mm HEI regardless of temperature, altitude, and fuel conditions. (Reference 2). The system requires minimum logistic support as well as multi-hit capability.
Configuration	This low-density ether-type reticulated-polyurethane foam is manufactured by the Scott Foam Division of Scott Paper Co., Chester, Pa. The pore size is currently available ranges from 25 to 50 ppi and is not covered by a MIL specification. Some of the significant physical properties for this type of foam are shown in Figure 7.
Availability	The foam can be supplied in bun form, 80 x 40 x 8 inches, or cut by the distributor to specified shapes and sizes, as required.
Additional Benefits	In addition to allowing free drainage, reticulated polyurethane foams also are non-wicking. They further permit free passage of air through the foam, where this may be required for ventilation and heat rejection around the fuel cell. Recent tests conducted by the Air Force (Reference 2) have indicated that this material, installed in a 2" deep void adjacent to the side of the fuselage fuel tank and under 5% compression may provide a reduction in hydraulic ram damage and subsequently aid in sealing self sealing tanks.
Disadvantages	The material will swell and lose some of its physical strength when subjected to long soak periods in hydrocarbon-type fuels. The continuous upper temperature limit is 375°F. The material is flammable and may support combustion especially when large skin damage occurs, as with HEI projectiles.

2.3.1.2 Closed-Cell Rigid Foam - Low-density, closed-cell rigid type foam consists of an expanded polyurethane and is designated by its manufacturer, AVCO, as 5I polyurethane foam. Figure 8 describes the physical properties of this material (Reference 3 & 4).

Property (1)	Units	Method	Parallel to Rise (2) Typical	Parallel to Rise (3) Specification	Perpendicular to Rise (2) Typical	Perpendicular to Rise (3) Specification
Density (4)	Lb/Ft^3	ASTM D1622	2.3	2.2 ± 0.5		
Compression Stress at:		ASTM D1621				
1.5% Offset	psi		24		15	
10% Strain	psi		21	16 min.	14	10 min
50% Strain	psi		24		18	
Modulus	psi x 10^6		0.00063	0.00047 min.	0.00031	0.00023 min.
Thermal Conductivity (at 250°F)	$\frac{BTU}{Hr\ Ft\ °F}$	ASTM C177	0.022			
Porosity (4)	%	Kerr Smith Pycnometer		5 max.		
Size 1 x 1 x 1 inches			9			
1.25x1.25 x 3.0 inches			2.5			

(1) Room Temperature values except as noted
(2) Typical - Arithmetic mean value
(3) Specification - Minimum (maximum) values or nominal values with tolerance limits.
(4) Density and porosity are independent of direction

FIGURE 8
SUMMARY OF PHYSICAL PROPERTIES
5I Polyurethane Foam

The basic operating principle for fire protection of a dry-bay adjacent to fuel tanks with rigid foam is simply to fill up the void so that fuel from a leaking or ruptured tank, if ignited by either a projectile-induced or electrical source is prevented from propogating into a destructive-type fire. When this space is filled, the oxygen supply to the spilling fuel is limited or eliminated in the internal segments of the aircraft, and fire in these areas will not readily propagate. In this respect, the designer is charged with the task of assuring that the rigid-foam material remains in place and does not break up too severely when impacted. This can be accomplished by reinforcing the material itself or containing the foam between layers of ballistic nylon cloth or other type binder. When rigid foam is used for application to dry-bay areas of four inches or less in thickness the volume is filled with the material for best results. Some computer tank modeling has been accomplished (Reference 5) using existing test data, with the resulting model description shown in Figure 9. In describing this figure it should be remembered that the direction of the projectile is through the foam. For design purposes, it should be pointed out that if the projectile can be expected from other directions, the foam as shown here must be placed along the entrance-exit plane of the tank wall.

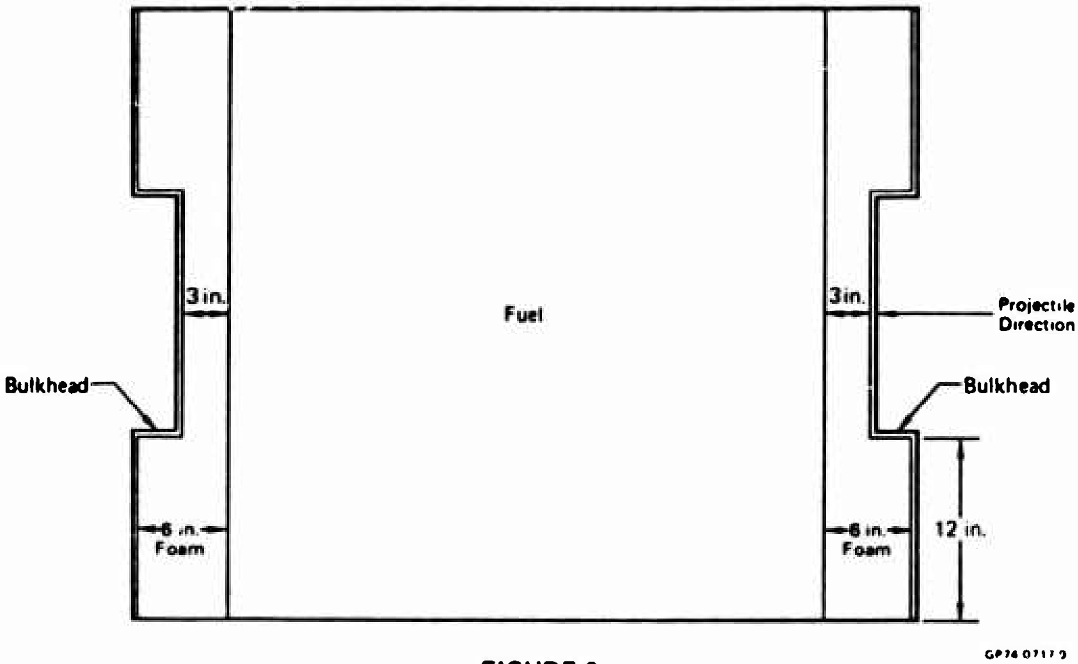

FIGURE 9
TOP VIEW OF GENERIC FUEL TANK

The generic tank model, shown in Figure 9, is fashioned to the 23mm HEI threat where the explosive warhead is initiated within the dimensioned perimeter of the tank. This particular model represents minimum rigid external foam application for the 23mm HEI threat, with the projectile attack direction through the foam. The tank is large and representative of a typical fighter fuselage or helicopter fuel tank. According to this data, in no case should there be less than three inches of material outside the tank, and the foam should be contained with a bulkhead as shown in the figure. Where other types of projectiles are used, or points of detonation from these projectiles occur at different locations, other considerations must be given. It has been found that if a high explosive round (23mm HEI) goes off in the foam itself, approximately 10 inches are required, as a radius dimension from the point of initiation, to offer fuel tank or dry bay protection. Armor-piercing incendiary (API) projectiles tend to core holes in the rigid foam materials. This was shown to be true in limited testing conducted by the AFFDL, where the installation of rigid foam in the dry bay areas around the fuel tanks successfully defeated the external fire potential for the 23mm HEI threat, but failed when subjected to the 23mm API due to coring of the material. An attempt to stop the coring and breaking up of this rigid material was made by applying a ballistic nylon cloth to both sides of the foam. This technique proved to be successful in limiting the breakup of the foam, but did not stop the coring. A layer of flexible foam or backing board next to the tank wall has been tested, and preliminary results indicate that dry-bay fire potential from API projectiles can be greatly reduced or eliminated.

In summary, each rigid foam design for dry-bay application must be qualified according to the test data available at this time. In all cases, the successful use of rigid foam type 5I for dry-bay application, requires the use of ballistic nylon cloth or other similar material bonded to each face of the foam. (Reference 6). This serves to hold the rigid material together when subjected to ballistic impact. It is also important to keep in mind that for the best results in dry-bay application, the bay should be completely filled. (Reference 5).

SYSTEM DESCRIPTION NARRATIVE CHART - CLOSED CELL RIGID FOAM

Principle of Operation	Suppresses fire by occupying the void adjacent to the fuel tank, thus eliminating the free air necessary to propagate and sustain fires.
Application Constraints	Must be cut or molded to fit the bay where it is to be applied. If lines, wires, or any other equipment are located in these areas, cut-outs must be provided. It cannot be applied in areas where cooling and ventilating air flow is required. It is recommended that the material either be reinforced or sandwiched between layers of ballistic nylon cloth to eliminate the effects of coring and breakup of the foam. It is also recommended that the dry bay volume be filled completely with the foam up to three inches in depth and that a minimum of three inches be used in larger voids to make the system effective.
System Performance	Provides excellent fire protection at all times, regardless of temperature, altitude, and fuel conditions, and will require a minimum of logistics support requirements. The design of the system is dependent upon the level of threat expected. Damaged sections should be replaced before they are subjected to a renewed hostile environment.
Configuration	The 51 foam is a closed-cell rigid polyester type polyurethane, exhibiting low friability but good mechanical strength, with a density of 2.3 pounds per cubic foot. It is a castable foam and can be supplied in a variety of shapes and sizes depending on its final use and requirements. It is provided with additives to give char stabilization and improved char yield upon exposure to large-scale fuel fires to block convective heat transfer. Evolution of reactive fire suppressant agents also occurs, which scavenge the free ions necessary in the hydrocarbon combustion process. The material may be cut to size and shape by the hot wire technique or by an electric knife. It is readily cut and easily adaptable to any size or shape cut-out.
Availability	The foam is available in various sizes and shapes, as it is a castable material that will form to the shape of its mold or container. Normally the designer would specify the required size and shape and have the supplier provide the foam accordingly.
Additional Benefits	When this material is used outside the fuel tanks, it may substitute as a tank backing board material, depending on the threat environment specified for the aircraft. It provides hydraulic ram structural protection, acts as a firewall, and aids in self-sealing by providing realignment of the wound through support of the tank.

Disadvantages Closed cell rigid foam acts as a wick and does not drain freely. It requires the use of ballistic nylon or other equal property type materials to be bonded to the faces for ballistic tolerance. This adds considerable weight to this type of system. Closed-cell foam cannot be applied to an area where air flow for ventilation or cooling is required. Normal aircraft in-flight vibration may tend to break up the rigid foam.

2.3.1.3 Purge Mats - Purge mats are flexible bags which occupy the entire void to be protected and are filled and pressurized with an inerting media. These mats consist of two layers of fabric impregnated with fuel-resistant rubber. Nylon drop stitches are woven into both sheets of fabric and retain the desired shape and thickness when the mat is inflated (Figure 10). Tests have shown that this concept is effective only at high pressures. Therefore the mat is constructed for operation in the 50 to 60 psi range.

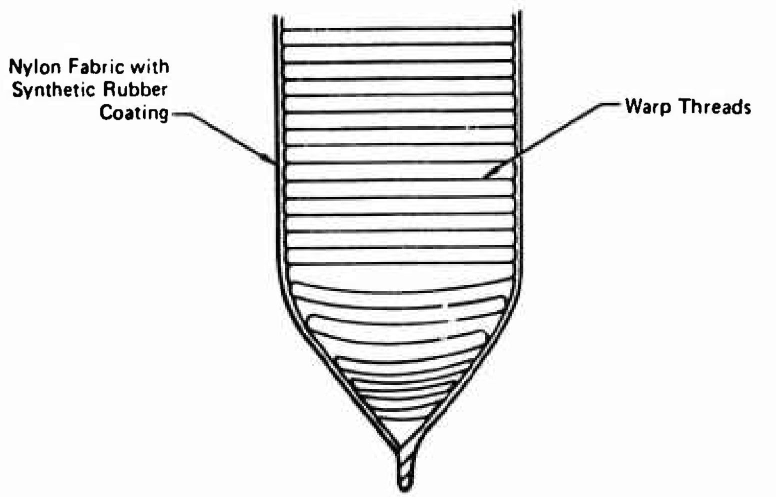

FIGURE 10
PURGE MAT (INFLATED)

The operation of purge mats is based on the release of the inert gas contained in the bag upon projectile penetration. The released gas inerts the immediate surrounding atmosphere where the fuel and ignition source are present. Fires associated with the leaking fuel and the incendiary ignition sources are thereby temporarily eliminated. This technique has been proven to be effective for small 0.30 and 0.50 caliber API projectile ignition sources, but for larger threats of the HEI type, the purge mat system is unsatisfactory. The reason for the failure of this technique against these large threats is due to the projectile blast, which in combination with the purge mat internal pressure, disperses the inerting gas more rapidly and over a larger area thus negating the inerting effect. This theory is supported by tests where the explosive in the larger projectile was initiated at some distance from the purge mat. The system in this case was successful in preventing fires. The following data (Figure 11) is taken from reference 7 and 8 and shows the results for gunfire testing of purge mats using the test setup shown in Figure 12.

Fuel: JP-4
Airstream 60/90MPH
Projectile Velocity: Service (Approx. 3000 FPS)
Inerting Mat Thickness: 3 inches
Inerting Medium: Nitrogen

Projectile	Function Distance, Inches	Mat Pressure psi	Fires/Fair Hits W Mat	Fires/Fair Hits W/O Mat
Cal. 0.50 Inc.	3	60	0/1	---
Cal. 0.50 Inc.	3	30	0/3	4/4
Cal. 0.50 Inc.	3	15	1/1	---
20mm HEI	3	60	3/3	---
20mm HEI	3	60	2/2	---
20mm HEI	3	50	1/1*	---
20mm HEI	3	30	1/1	2/2
Cal. 0.50 Inc.	28	60	0/2	2/2
Cal. 0.50 Inc.	33	--	---	1/1
20mm HEI	30	60	0/2	2/2
20mm HEI	30	--	0/1	---
Cal. 0.50 Inc.	14	--	---	1/1
20mm HEI	14	--	---	0/1**
20mm HEI	14	60	1/2	0/1
20mm HEI	38	60	0/1	---

* Cell had plexiglass front which broke
** Flash fire for 1 or 2 seconds

FIGURE 11
FIRE TEST OF INERTING MATS

More recent data indicates that if a fire extinguishing powder is substituted for the nitrogen gas in the purge mats, a higher degree of effectiveness against larger caliber threats is possible. In this case the powder does not automatically escape through the wound, but is in fact evenly distributed throughout the protected area by the subsequent hydraulic shock, providing better fire suppressing capability. (Reference 9)

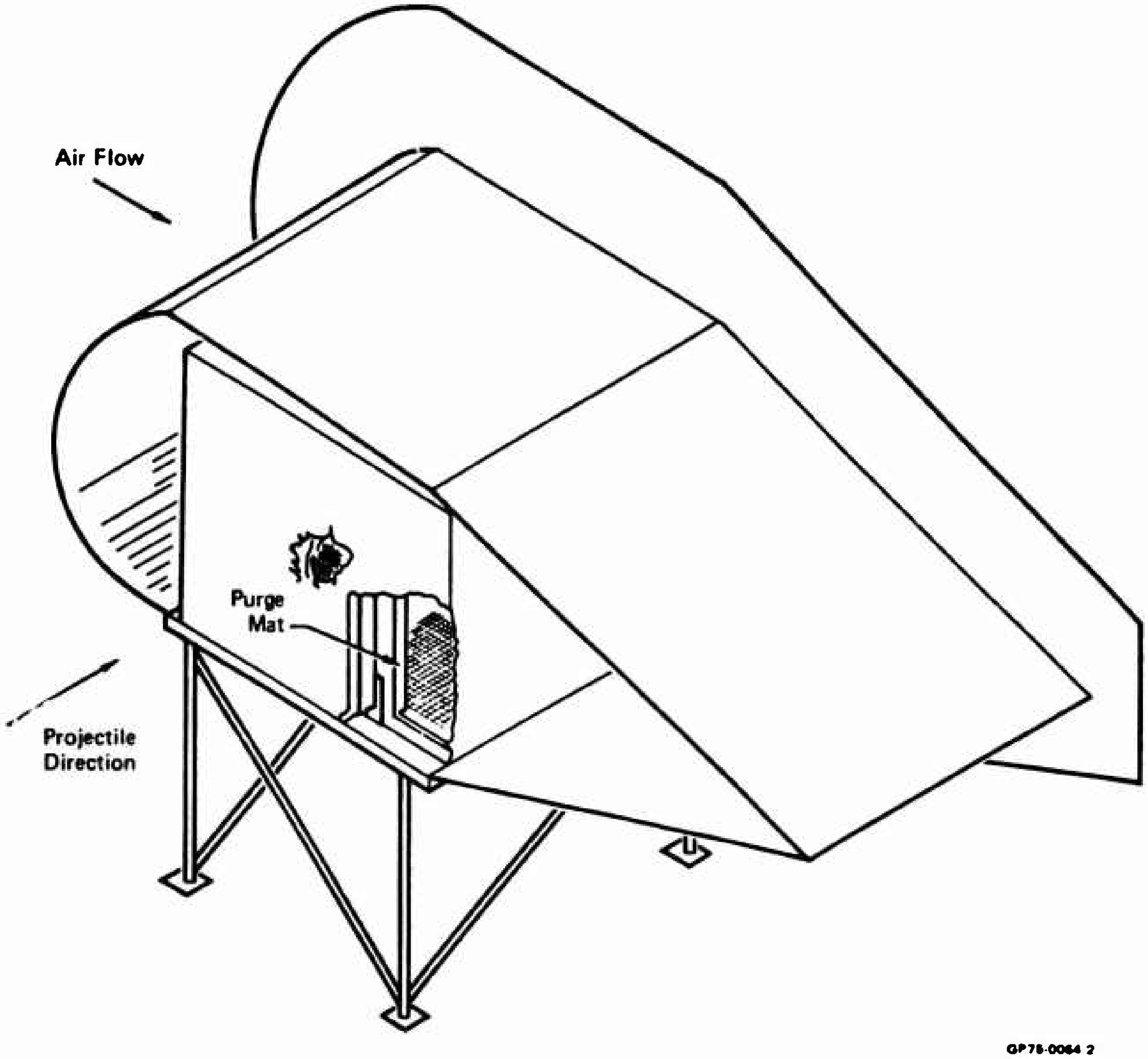

FIGURE 12
GUNFIRE TEST SET-UP FOR PURGE MAT EVALUATION

SYSTEM DESCRIPTION NARRATIVE CHART - PURGE MATS

Principle of Operation	The purge or inerting mats consist of inflated bags, located outside the fuel cell and filling the void volume. Projectile penetration through the bag or mat into the fuel cell releases and provides an inert atmosphere, thus preventing sustained fires. In tests of the system, nitrogen has been used most frequently as the inerting agent, although suitable halogenated hydrocarbons, such dibromodifluoromethane (Halon 1202), could also be used. Fire extinguishing powders may be substituted in place of the gas.
Application Constraints	Design mat or mats to fit contours of the bay. Cut-outs are not required for equipment and plumbing except where distortion or mechanical interference effect operational safety.
System Performance	Provides fire protection on a limited basis only, depending upon the size of the threat and the respective location of threat initiation. It is also a single-hit system, as presently designed. (References 7 and 8) Powdered filled mats appear to work better than the gas filled mats. (Reference 9)
Configuration	Typical construction consists of an envelope of fabric impregnated with a fuel-resistant rubber reinforced with nylon drop stitches between the fabric walls to retain the desired shape and thickness when the mat is inflated. The gas filled mats have an approximate specific weight of 0.25 lb. per square foot and are designed for an operating pressure of 50 to 60 psi with a burst pressure in excess of 100 psi. Powder filled mats need not be pressurized.
Availability	Must be fabricated by the supplier to specified shapes and sizes as required.
Disadvantages	The gas filled bag system to date does not perform with contact fused high-explosive threats, such as 20mm HEI, and must be limited in application where air flow in the dry bay is not required. It is difficult to install where tank walls are not flat and where wire bundles, control cables, and tubing are routed through these dry-bay areas.

2.3.1.4 Fire Extinguishing Systems - Dry bay fire extinguishers are used in compartments which contain combustible fluids or are adjacent to fuel tanks. The design of these systems is dependent on a number of parameters including; toxicity, thermal stability, corrosion, storage, quantity requirements, stay time and effectiveness. Toxicity is a factor where the extinguishant can penetrate habital areas or when release of the agent occurs in an enclosure, such as a maintenance hanger. The toxity of the most commonly used agents have been evaluated by several agencies and the data is published in AFSC DH-1-6 system safety design handbook. Halons 1301, 1211, 1011, 1202, and 2402, are most commonly used and are listed here in increasing order of toxicity.

Thermal stability, storage and corrosion data are also available in a number of references (10 through 15). Halons 1301 and 1202 are the most thermally stable agents.

The agent quantity required to extinguish a dry bay fire depends upon the particular agents effectiveness i.e. volume percent required to extinguish a fire and the air change per unit time in the compartment, along with the specified (MIL-E-22285) stay time of one-half second. A good analysis of concentration versus time and quantity of agent needed for vented or damaged compartments is contained in Reference 16. A generalized formula for agent quantity has been devised which accounts for the properties of the specific agent to be used.

The basic properties of the agent such as vapor pressure, freeze point viscosity, etc. effect the design of the storage and dispensing equipment. Environmental conditions of -65°F to maximum compartment temperature effect fill ratio and material compatibility, maximum design pressure and weight of the system. Under cold condition, if the agents vapor pressure is insufficient to propel it, nitrogen pressurization is used. Nitrogen pressurized systems generally use 600 psi nitrogen at ambient temperature. This pressure increases with temperature imposing a considerable weight penalty on the system. Another approach is to use a pyrotechnic generated gas to pressurize the system. Such systems are lighter and use less volatile extinguishing agents.

The primary disadvantages of extinguishing systems are; reliably in detecting a fire, providing protection against rekindeling fires (single shot versus multiple shot systems) and maintenance of the storage vessel. The latter requires routine inspection to see that it is fully pressurized and has not leaked or been expended. In the case of dry bay compartments with high air flows extinguisher systems may weigh more than passive baffeling systems.

SYSTEM DESCRIPTION NARRATIVE CHART - FIRE EXTINGUISHING

Principle of Operation	The extinguisher type fire suppression system is a lightweight active technique in which an extinguishant is released into the fire zone upon detection of the fire by its sensors. Halons 1301, 1211, 1011, 1202, and 2402 are the most commonly used extinguishants. Detectors are normally optical sensing devices installed in sufficient quantity to allow light detection at any location in the tank.
Application Constraints	This system must be installed so that complete coverage of the entire void volume by the extinguishant is accomplished. Application of this system should be limited to large dry bays rather than the small void volumes adjacent to the tanks as individual bottles are required for each segmented area.
Configuration	The extinguishing system consists of a self-contained unit made up of a high pressure bottle containing the extinguishing agent and a detection device, usually an optical sensing device designed to trigger an explosive charge that releases the agent from the bottle. In most cases the extinguishant is manually released.
Availability	Equipment for this type system is readily available although improvements in detectors are required to make the system operational for high energy fuel-vapor ignition sources.
Disadvantages	Logistics for this type system is high since the bottles must be replaced following activation. Periodic inspection of the bottles is also required to insure that inadvertant activation has not occurred.

2.4 EXPLOSION PROTECTION TECHNIQUES

Fuel tank explosions are a result of ullage deflagrations where the combustion over-pressure generated exceeds the structural strength of the tank. Explosion protection techniques, therefore, fall into several categories including inerting, extinguishing, fire suppression and over-pressure attenuating. These systems are further classified as passive and active. Passive systems are those which require no activation, mechanical or logistic support to maintain their operating capability, making them effective on an around-the-clock basis. Foam or other void filler-type materials, as well as modified fuels are included in this category. Nitrogen inerting, halon extinguishant, and fuel fogging systems are included in the active system category. State-of-the-art explosion protection systems and the required materials and equipment are described in the following paragraphs:

2.4.1 State-of-the-Art Explosion Protection Techniques

2.4.1.1 Reticulated Polyurethane Foam (MIL-B-83054A) - Foam explosion protection system design varies with the physical properties of the material, the degree of protection required, and the installation access. The material is a polyester-based urethane linked compound, reticulated to an open-celled configuration, and is approximately 98 percent void. The fibers forming the cells in the foam occupy about 2 percent of the volume of the bulk material (Figure 14). The size of the pores or openings in the foam varies inversely with the number of pores per linear inch (ppi) which ranges from 10 to 25 ppi, and may be held to a tolerance of +3 ppi and -2 ppi. Foams with different pore sizes are used for the same purpose, but the thickness required to eliminate flame propagation and therefore the amount needed to protect any particular tank volume varies according to the pore size. The smaller pore size (25 ppi) material may be cored or voided to larger degrees than the larger pore size (10 to 15 ppi) foams, while offering the same degree of protection.

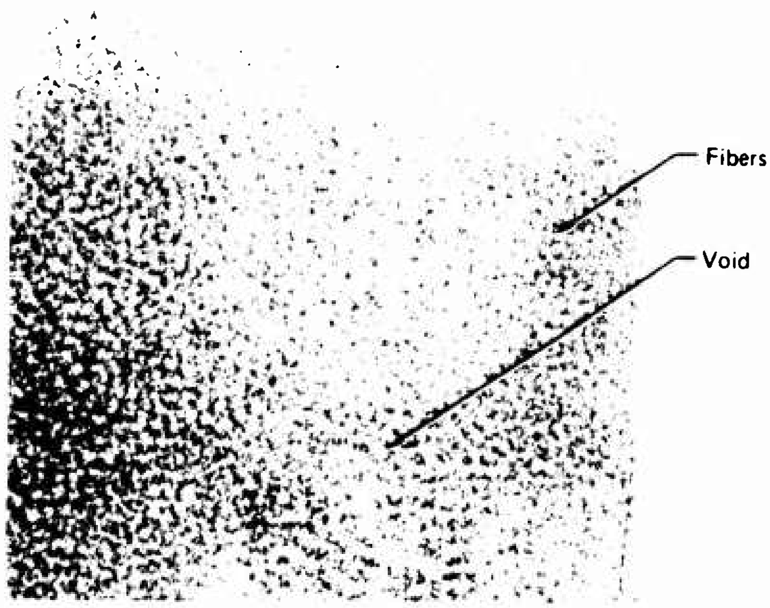

FIGURE 13
POLYURETHANE RETICULATED FOAM

Materials densities and fuel-retention values also vary for the materials with different pore sizes. Materials with smaller pores generally have a greater fuel-retention because of their greater fiber surface area, but as previously mentioned they can be voided, which offsets the weight and fuel volume penalties associated with their use. Physical property descriptions of these materials is given in Figure 14 of this section.

2.4.1.1.1 <u>Fully Packed Foam Explosion Protection Concept</u> - A fully packed system is defined as one where all potential combat tank ullage is filled with foam with cutouts for equipment only. This system is desirable where little or no tank over-pressure can be tolerated, for example, aircraft fuselage fuel tanks. The yellow 15 ppi or red 25 ppi foam can be used for this application (Reference 6). However, the yellow foam is recommended because of its lower fuel retention penalty since the same degree of protection is provided by both materials in a fully packed installation. This material is presently specified by MIL-B-83054A (USAF), dated 15 August 1973. A description of the physical properties is given in Figure 14, followed by a system description narrative.

	Yellow (15PPI)	Red (25PPI)
Density range (lb/ft^3)	1.35 ± .1	1.2 to 1.45
Porosity (pores per inch)	8 to 17	19 to 30
Air pressure drop (in. of water per in. of mat'l)	0.014 to 0.220	0.240 to 0.330
Tensile strength (psi)	15 (min)	15 (min)
Tensile stress at 200 percent elongation (psi)	10 (min)	10 (min)
Ultimate elongation (percent)	220 (min)	220 (min)
Tear resistance (lb/in.)	5 (min)	5 (min)
Constant deflection compression (percent)	35 (max)	35 (max)
Compression load deflection at:		
25 percent deflection (psi)	0.30 (min)	0.30 (min)
65 percent deflection (psi)	0.50 (min)	0.50 (min)
Load deflection curve from 0 to 80 percent deflection	ASTM D1564-1 (Suffix D) 25 and 65 percent deflection level	ASTM D1564-71 (Suffix D) 25 and 65 percent deflection level
Fuel displacement (volume-percent)	2.5 (max)	2.5 (max)
Fluid retention (volume-percent)		
Fuel	2.0 (max)	3.0 (max)
Water	7.0 (max)	10.0 (max)
Flammability (inches per minute)		
ASTM D1692-59T	15 (max)	15 (max)
ASTM D1692-68	Report	Report
Extractable materials (weight)	3% (max)	3% (max)
Volume increase after fluid age		
Type I fluid (volume-percent)	0-5	0-5
Type III fluid (volume-percent)	0-12	0-12
Grade JP-4 turbine fuel (volume-percent)	0-10	0-10
Low temperature flexibility (-40°C)	No cracking or breaking of strands	No cracking or breaking of strands
Entrained solid contamination (milligram/ft^3)	110 (max)	110 (max)
Steam autoclave exposure (tensile loss in percent) (1 hr @ 140°C)	40 (max)	40 (max)

FIGURE 14
PHYSICAL PROPERTIES AND CHARACTERISTICS

SYSTEM DESCRIPTION NARRATIVE CHART - FULLY PACKED RETICULATED FOAM

Principle of Operation	Suppresses explosions and flame fronts by absorbing radiant and sensible heat on its large complex surface created by the foam cell webs. Reduces the normal turbulence and mixing action that is characteristic of an unrestrained flame front to a point where the reactive collisions between the fuel and oxygen molecules occur at too slow a rate to allow flame propagation. The heat of combustion of the few reactions that do occur has sufficient time to be absorbed by the air-fuel foam environment. Some pyrolysis of the foam does occur in this process, but little, if any, damage to the foam is evidenced.
Application Constraints	Install under 3 to 5 percent compression. Design and cut foam to fit the contour of the tank with cutouts for equipment and plumbing. Cutout areas should allow a minimum of one inch of space around pumps, valves, etc., for ease of flow and venting in these areas. The use of hot wire cutting is suggested for major sculpturing since this method reduces particulate contamination; however, for smaller cuts and voids, the use of electric carving knives is permitted. A final cleaning is suggested which involves rubbing each foam piece over a frame-mounted mesh screen or hardware cloth to dislodge any frayed or loosened foam particles on the surface. Strict handling and storage procedures are required to minimize contamination and degradation of the foam. During installation, detailed inspection procedures are required to assure a proper fit, especially in component and void areas. This is required in order to eliminate any interference with working components and system performance. As a final check on the installation, each aircraft is tested to assure proper fuel system operation. This acceptance testing normally involves such items as fuel quantity gauge recalibration, booster pump performance, vent testing, and contamination checks. In addition to these acceptance tests on each aircraft, the first prototype aircraft which is modified should be tested in detail to demonstrate the adequacy of the basic foam design for that particular aircraft fuel system. This testing involves the acceptance test mentioned, and other tests, including the establishment of new tank capacities, usable fuel quantities, and gross weight changes.

System Performance	Excellent explosion suppression. Provides complete explosion protection at all times, regardless of ignition source, temperature, altitude, and fuel condition. The system requires minimum logistic and maintenance support.
Configuration	The present foam material, designated "Scott Safety Foam" because of its application, is basically low-density, reticulated, polyester-polyurethane that is produced by a special process in which all the membranes are eliminated by thermal reticulation from the conventional strand and membrane structure. The resulting structure is an open pore, three-dimensional, skeletal network of strands having a nominal pore size of 15 pores per linear inch (ppi) and a density of about 1.4 pounds per cubic foot. It is produced by the Scott Foam Division of Chester, Pa., and is distributed by Firestone, Goodyear, and US Rubber (Uniroyal) tire and rubber companies. Procurement by the Air Force is based on the requirements of Specification MIL-B-8305A (USAF).
Availability	The foam can be supplied in "bun" form, 80 x 40 x 8 inches in size, or cut by the supplier to specified shapes and sizes as required.
Additional Benefits	Other benefits derived from the use of fully packed foam systems include surge and slosh mitigation, as well as aiding the alignment of wounds in self-sealing fuel tank walls; thus increasing the margin of effectiveness in sealing ability. Cursory testing also indicates that the effects of hydraulic ram from projectiles may be reduced. This system also provides for multiple hit capabilities of both a simultaneous and a separate nature.
Disadvantages	Data to date indicates that the life of this material is approximately 5 years in an environment of high temperature (95°F) and high humidity (95%) if the foam is used inside fuel tanks and is wetted. Under a tropical environment as experienced in Southeast Asia; however, the life is reduced to 3 to 3 1/2 years. Newer blended ether/ester based polyurethane foams show promise of greater life expectancy.

2.4.1.1.2 Voided Foam Explosion Suppression Concept - Voided foam concepts are used where overpressures can be tolerated in the fuel tanks. The higher the allowable tank overpressures, the greater the possible foam voiding. There are two basic ways to apply this technique, which can result in up to 95 percent decrease in the quantity of foam required to protect the tanks. The first approach provides integral isolation (compartments or voids within the foam), while the other takes advantage of natural structural compartmentalization. The integral isolation concept lends itself to large fuselage or wing type fuel tanks where subdividing the tank into intercommunicating compartments is accomplished with the foam itself forming the walls of the individual cells. Foam is used to isolate the fire and/or explosion to the combustion cell (cell where ignition occurs) by acting as a flame arrestor and preventing the flame from propagating to the adjacent cells. This allows the remaining voids as well as the foam itself to serve as relief volumes; thus reducing the combustion overpressure. This mechanism permits system design based on allowable tank pressures where combustion volumes, relief volumes, and required foam thicknesses govern the allowable percentage voiding. Figure 15 shows a variety of possible integral isolation foam concepts. The concepts shown represent designs where the particular fuel tank is empty of liquid fuel. Where fuel tanks are partially full only the ullage space at any design angle of attack need be protected with foam. This ullage foam in turn may be voided for additional weight saving.

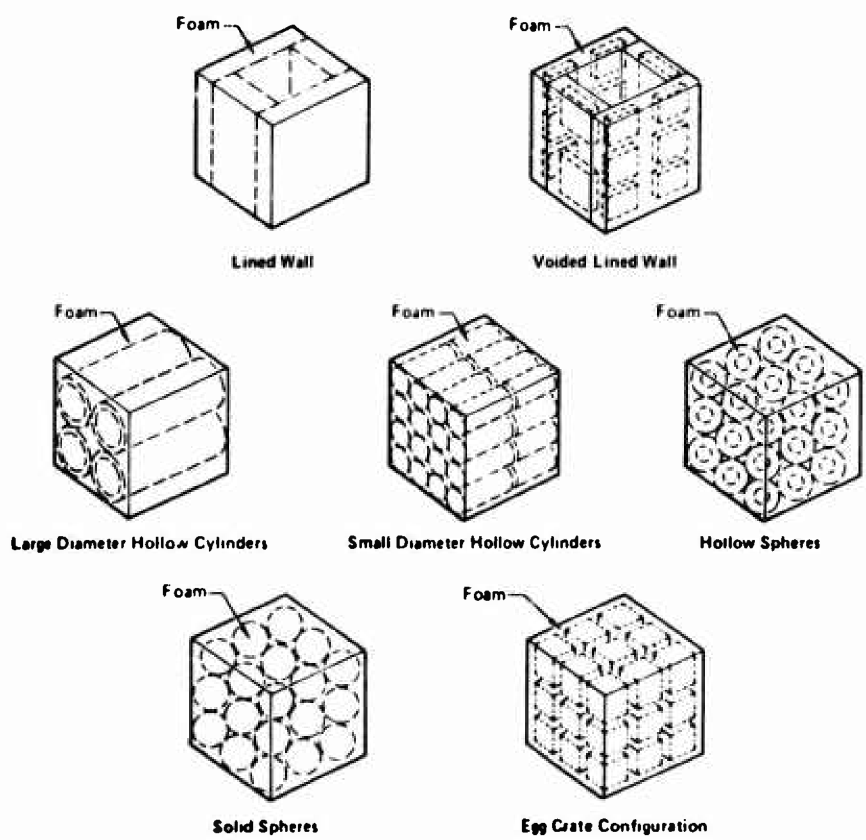

FIGURE 15
INTEGRAL ISOLATION CONCEPTS

Fifty percent void foam systems have been successfully proven and qualified for use in fighter-type aircraft fuselage fuel tanks where tear-resistant bladder material is used for the tank itself and skin/stringer-type construction is used for the airframe (Reference 16). Higher percentage void systems are possible, but the design requires additional test data, based on the geometry of the tank and the pressure limitations on the structure.

The simplest model of a relieved explosion depicting the integral-type design is shown in Figure 16. In this model, V_c is the combustion volume and V_f the arrestor volume. The relief volume V_r is supplied by the arrestor material only. If, however, the depth of the arrestor material is greater than that needed to stop flame propagation, voiding behind the arrestor material is possible as shown in Figure 16B. The total relief volume (V_r) now is V_r plus V_f with basically no change in the model parameters.

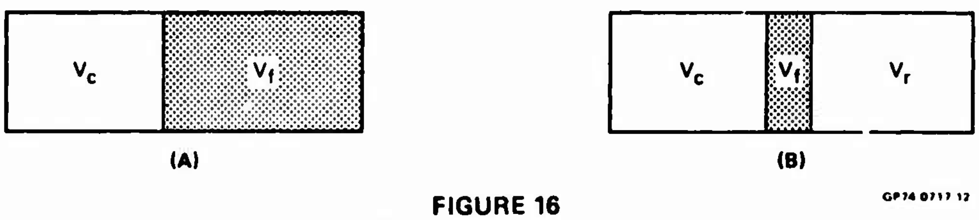

FIGURE 16
SINGLE TANK MODEL

Since the combustion of hydrocarbons with air, little or no change occurs in the average molecular weight or total moles of gas present, the following relationship can be assumed to be true:

$$P_1V_1/T_1 = P_CV_C/T_C = NR = CONST. \qquad (1)$$

where subscript 1 refers to initial conditions and subscript C refers to final conditions.

Further, since the maximum ratio of (T_C/T_1) is eight for most hydrocarbon/air stoichiometric mixtures of interest and is independent of all other model parameters, it is considered a constant (K) in the analysis. Thus the combustion process can be written as:

$$KP_1V_1 = P_CV_C \text{ or } P_C/P_1 = K \text{ where } V_1 = V_C \qquad (2)$$

The above equation is satisfactory for unrelieved explosions; however, when free adiabatic expansion is allowed and flame propagation is limited to the available combustion volume, as assumed in this model, two possible solutions to the attenuated model exist. The first assumes that all of the combustible gases in (V_C) burn and expand to equilibrium in the total volume. This solution results in the maximum predicted pressure rise for the attenuated model. Experimental work has shown this solution to be invalid.

The second solution assumes that only a portion of the combustable volume (V_x) burns venting part of the original unreacted volume through the foam into the protected relief volume (V_r). Introducing (V_x) into the model and using the nomenclature shown in Figure 17 below, yields the following relationships:

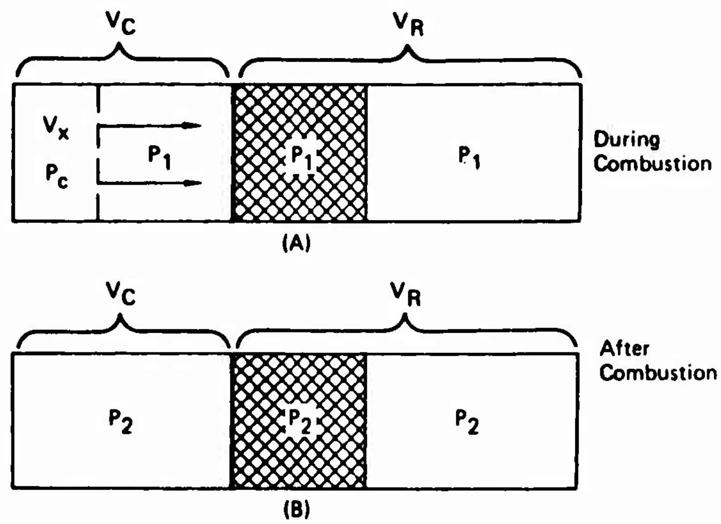

FIGURE 17
THEORETICAL MODEL

$KP_1(V_x)^N = P_2(V_C)^N$ $\quad$ P_2 = final pressure $\quad$ (3)

$V_x \to V_C$ = adiabatically

N = specific heat ratio

$P_1\ [V_r + (V_C - V_x)]^N = P_2\ (V_r)^N$ $\quad$ (4)

Using relationships (3) and (4), solving for P_2/P_1 yields:

$$\frac{P2}{P1} = \left[\frac{V_r/V_C + 1}{(\frac{1}{K})^{1/N} + V_r/V_C}\right]^N \quad (5)$$

When (V_r) equals zero, i.e., an unrelieved explosion, equation (5) reduces to:

$$\frac{P_2}{P_1} = K$$

which is identical to equation (2) and therefore P_2 for this case equals P_C.

Although equation (5) is for ideal gases and does not account for heat loss or flow restriction, correlation with experimental data is quite good. (Figure 18)

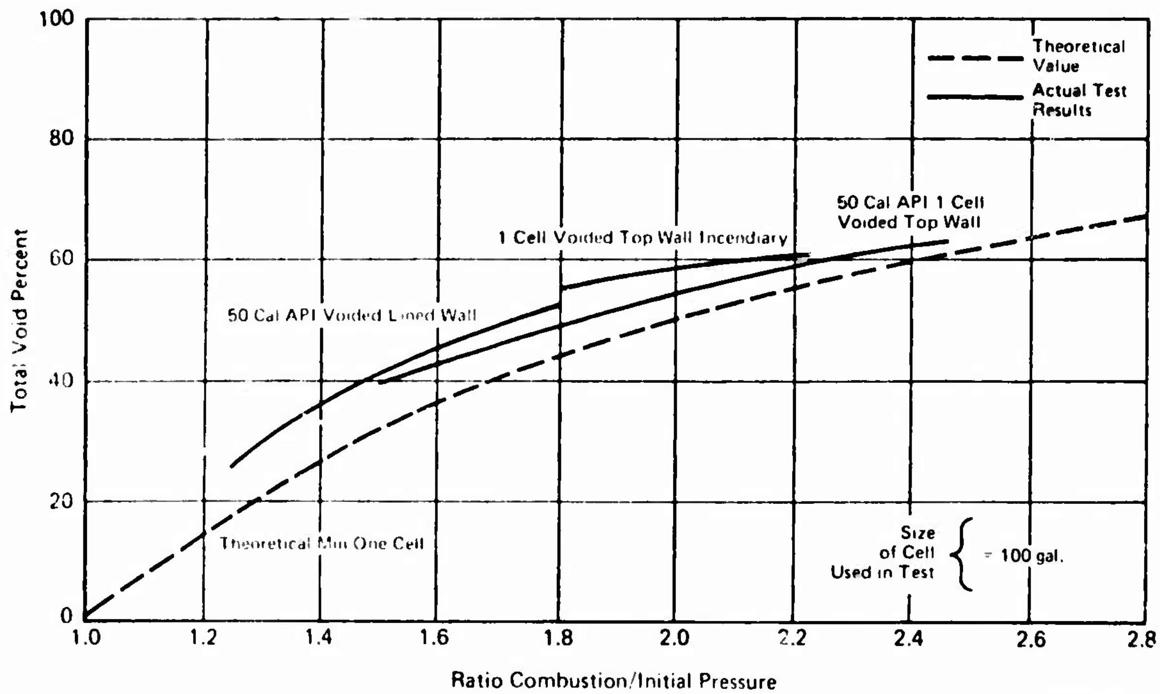

FIGURE 18
FUEL TANK GROSS VOIDED FOAM
GUNFIRE AND INCENDIARY DATA
(Single Cell)

Divergence of the predicted overpressure values of the model occur as the mass transfer resistance to the relief volume increases. The resistance is a function of the mass transfer rate which in turn is influenced by the size and type of ignition source, the initial pressure, the combustion volume and the relief area and volume. To accommodate the mass transfer rate and resistance a dynamic model has been formulated and is included in Reference 18. For single cell protection the static model satisfactorily predicts the results for up to 60 percent voiding. Where structural compartmentization is used as described below, the relief area to combustion volume must be considered and dynamic effects may alter the results. In any case, the maximum overpressure can be predicted by considering each cell individually.

The structural isolation concept is readily applicable to integral wing fuel tanks where the structure offers natural compartmentalization, with intercommunicating openings between cells. Foam is placed over these openings and is used to isolate the reaction in the combustion cell by acting as a flame arrestor, stopping the flame propagation to the adjacent cells. Pressure generated by the combustion process in the ignited cell is relieved through the foam and intercommunicating holes. The parameters of combustion volume, relief volume, and foam thickness, as well as ignition energy and intercommunicating hole size, as they relate to allowable tank pressures, govern the design of this type system.

Where systems, as shown in Figure 19 are applied to wing-type tanks, considerable voiding (up to 95 percent) is possible.

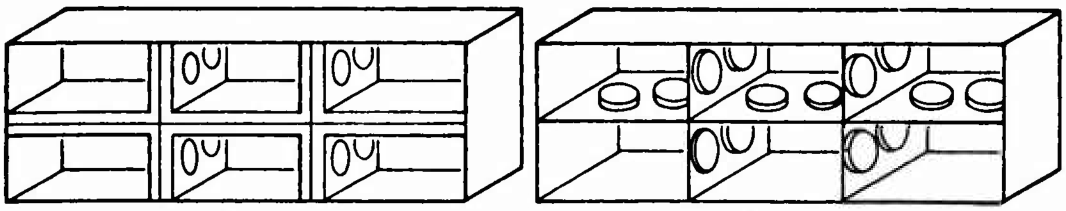

FIGURE 19
STRUCTURAL ISOLATION CONCEPTS

Overpressures are increased, but are acceptable because of the higher allowable structural limits for most wing primary structure areas. If the intercommunicating holes are small (less than the 5-10 percent of wall area), as is normally the case, relief is restricted and the pressure in the combustion cell exceeds predictions as previously discussed. This was shown to be the case where full-scale gunfire tests (References 19 and 20) on a simulated wing structure produced data indicating that each cell, protected as shown in Figure 19A or 19B, acts as a separate unit divorced from the adjacent cells, from a relief standpoint.

Smaller ignition (spark) sources cause fire propagation at a slower rate; thus allowing flow and relief through the intercommunicating holes. Increasing the hole size will also allow more flow, but alters structural design and can result in increases in weight by requiring heavier skins or internal reinforcing members to maintain the aerodynamic-structural requirements. The result is usually a compromise where additional foam is added to reduce the combustion overpressure. This reduces the allowable combustion volume for any given cell and adds assurance that burn-through of the foam to the adjacent cells does not occur (Reference 21). In the case of no burn through for this multicelled type system the theoretical minimum pressures agree very closely with actual test results. (See Figure 20). The divergence of the test data from the theoretical values in most cases is due to the slight amount of burning that takes place in the foam itself raising the predicted pressure slightly.

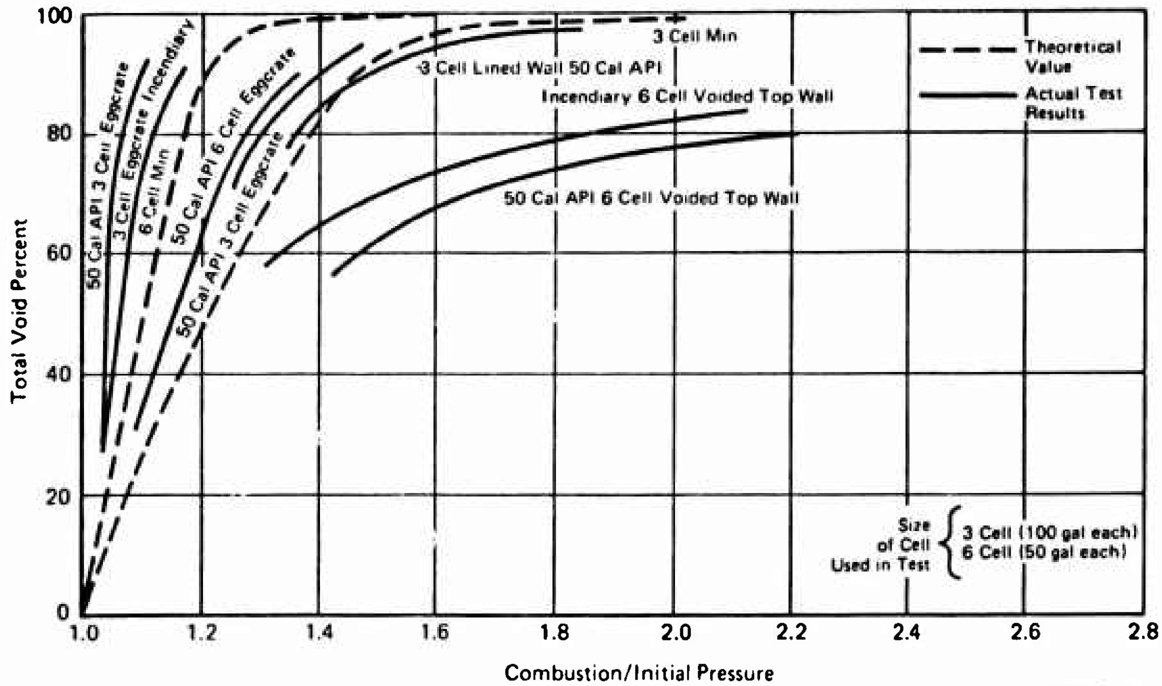

FIGURE 20
FUEL TANK GROSS VOIDED FOAM
GUNFIRE AND INCENDIARY DATA

Current design techniques for wing tank type explosion protection systems use up to 80 percent voiding (20 percent foam by volume) and have been qualified through 0.50 caliber API gunfire tests.

The theoretical model relating overpressure to volume of relief and volume of combustion assumes that the polyurethane foam successfully prevents flame penetration into adjacent voids. Unfortunately, there is no model to predict the thickness of foam required to prevent flame penetration. Experimental results must be relied upon to determine the thickness required for any voiding configuration consisting of multiple voids and/or large voiding percentages.

Both incendiary pellet and gunfire test data indicates that 25 ppi (Red) reticulated polyurethane foam as specified in MIL-B-83054A (USAF) provides the best overall performance. Following is a system description narrative which outlines the basic design parameters for the integral and structural type foam protection systems.

SYSTEM DESCRIPTION NARRATIVE CHART - VOIDED RETICULATED FOAM INTEGRAL ISOLATION CONCEPT

Principle of Operation	Allows an explosion to occur, but limits it to small internal void volumes, relieving the generated combustion pressure into adjacent cells; thus reducing total system overpressures to a level within the structural limits of the airframe. Isolation of the combustion cells is accomplished by geometric design of closed foam containers with walls of sufficient thickness to stop flame propagation. Fifty percent void systems have been qualified against 0.50 cal API and high velocity fragment threats for this type design on fuselage-type tanks. Where this foam weight and volume is prohibitive to the particular aircraft design, greater voiding may be accomplished by reducing foam wall thickness and increasing the void volume. In so doing, increased overpressures result as burn-through occurs and adjacent void volumes are ignited. The resulting increased overpressures are not linear with respect to the combustion and relief volume relationships, as the delay of the flame front caused by foam walls allows previously burned voids to act as relief volumes for the adjacent cells.
Installation Constraints	Install under 3 to 5 percent compression. Design and cut foam pieces to fit the contour of the individual tank with cutouts for equipment and plumbing. Voiding design must consider structural integrity of the foam after installation process to insure that the void volumes are not collapsed due to the compression fit. No adhesive is required for proper installation. Cutting techniques and acceptance tests and procedures are identical to those defined previously in the open cell flexible foam fire protection narrative chart. System must be designed and installed to prevent cascading of foam into void areas from violent aircraft maneuvers.
System Performance	Excellent explosion suppression and overpressure control device. Provides protection at all times but voiding may be limited if the HEI ignition source is considered. This type of system can be tailored to the tank and structure to provide considerable weight savings by the voiding technique. Verification testing of the system's performance is necessary for large voiding percentage.

Configuration	The present foam material, designated "Scott Safety Foam" because of its application, is basically low-density, reticulated-polyester polyurethane that is produced by a special process in which all the membranes are eliminated by thermal reticulation from the conventional strand and membrane structure. The resulting structure is an open-pore, three-dimensional, skeletal network of strands having a nominal pore size of 25 pores per lineal inch (ppi) and a density of about 1.4 pounds per cubic foot. It is produced by the Scott Foam Division of Chester, Pa., and is distributed by Firestone, Goodyear, and U.S. Rubber (UniRoyal) tire and rubber. Procurement by the Air Force is in accordance with Specification MIL-B-83054A (USAF).
Availability	Can be supplied in "bun" form, 80 x 40 x 8 inches in size, or cut by the distributor to specified shapes and sizes as required.
Additional Benefits	Some fuel surge and slosh mitigation occurs and alignment of wounds in self-sealing fuel tank walls are other benefits derived from the use of this system. It also provides for multiple hit capability, both simultaneously and at spaced intervals, as well as logistic-free operation. Simultaneous hits may result in slightly higher overpressures for reasons described in Section 4.1.1.2. Some blast attenuation is also obtained.
Disadvantages	The urethane polyester base material is hydrolytically unstable as indicated in Reference 4. High temperature and humidity greatly reduces its life, for example, Southeast Asia conditions resulted in a 3 to 3-1/2 year life. Newer foam material using a blended ether/ester linkage promises to increase the life of the material by 2 to 5 times the current figures.

SYSTEM DESCRIPTION NARRATIVE CHART - VOIDED RETICULATED FOAM STRUCTURAL ISOLATION CONCEPT

Principle of Operation	Allows an explosion to occur, but limits it to the combustion cell and attenuates the overpressures to a level below the structural limit of the tank. Isolation is accomplished by either the geometric design of closed foam containers and their place ment in the individual cells, or by utilizing the natural structural compartmenalization in wing-tank-type design in which, the intercommunicating holes are covered, as well as to stop flame propagation. Combustion overpressures are controlled by the amount of foam and the size of combustion volumes, all somewhat regulated by the design of the structure. Cutting techniques and acceptance tests and procedures are identical to those defined previously in the 15 ppi foam narrative chart.
Installation Constraints	Installation of the lined-wall and plug-type configuration required the use of an adhesive to bond the foam to the structure and seal any possible flame path created by improperly cut foam material or interfering structure. Several types are available, but care must be taken in selection for compatibility and weight of the adhesive. The design and installation be such that any cell to cell communication must be through the foam barrier. See description narrative chart, integral isolation concept.
Configuration Availability	See description narrative chart, integral isolation concept. The foam can be supplied in bun form, 80 x 40 x 8 inches in size, cut by the distributor to specified shapes and sizes are required.
Additional Benefits	Fuel surge and slosh mitigation, multiple-hit capability, logistic-free and multiple-mission capability are benefits of this type system.
Disadvantages	See description narrative chart - Integral Isolation Concept

2.4.1.2 Nitrogen Inerting (Liquid Nitrogen Source) - There are basically three state-of-the-art systems capable of providing nitrogen to the ullage. These are:

(1) Closed Vent - Where nitrogen is fed into the tank ullage as the fuel is used.

(2) Open Vent - Where a sweeping action is utilized to reduce the oxygen concentration of the ullage.

(3) Scrubbing - Where fine bubbles of nitrogen are formed in the bottom of the fuel tank to remove the dissolved oxygen.

Two storage and supply systems for nitrogen exist; i.e., cryogenic liquid and high pressure gas. For the purpose of this report, only the liquid nitrogen storage system will be considered, as it is considerably lighter in weight.

In nitrogen inerting systems for aircraft-type fuel tanks, the parameters of mission profile and tank ullage in the combat environment play an important role in sizing the system. The mission profile dictates the number of excursions to altitude and thus the quantity of nitrogen lost through the pressure and vent sequences. The tank ullage at combat defined by the mission profile, describes the required volume to be maintained in an inert condition. Two things must be considered in rendering a fuel tank system inert by nitrogen dilution. The first is the tank ullage volume which must be purged with nitrogen, and the second is the fuel itself, which must be scrubed with nitrogen to remove the dissolved oxygen. Oxygen is introduced into the tank ullage through the pressure and vent system during aircraft flight. The fuel absorbs an amount of air, dependent upon the total pressure, and as the aircraft gains altitude, some of the dissolved gases will be expelled. The solubility coefficients are such that the dissolved gases in the JP-4 fuel contain 35 percent oxygen, and when these gases are expelled, oxygen enrichment of the ullage occurs. When this occurs without nitrogen dilution of the evolving gases, the oxygen concentration will exceed the safe level. In order to prevent supersaturation and subsequent oxygen release, the fuel is scrubbed by injecting very small bubbles of nitrogen into it. The large surface area of the bubbles and the long contact time allows equilibrium diffusion to occur in each bubble; thus scrubbing out and diluting the dissolved oxygen.

The oxygen concentration is the governing parameter in the successful operation of a nitrogen inerting system. It has been shown that if the oxygen concentration in the vapor space can be reduced below 12 percent by volume, flame propagation does not occur. At a 12 percent oxygen concentration, and using 0.50 caliber API projectiles as the ignition source, combustion occurs within the incendiary plume, but does not propagate throughout the ullage. Associated with this combustion is an overpressure that may rupture the tank, depending on the size of the tank and its allowable structural limits. In these cases the volume of gas ignited by the ignition source compared to the volume of the tank must also be considered, in addition to the oxygen concentration. The data in Figure 21 was obtained using a 100 gallon test tank. As the volume of this tank is increased the total overpressure from combustion will decrease. Further relief of the overpressure is accomplished as venting occurs through the projectile entrance and exit holes and will vary according to the size of these holes. These overpressures are reduced as the oxygen concentration is reduced, but are never negated completely (Figure 21 and Reference 22). Design of a nitrogen inerting system is based simply on filling the ullage with nitrogen as the aircraft uses fuel and changes altitudes, and scrubbing the fuel with nitrogen bubbles through these same excursions. A simple PVT relationship is used to determine the required quantity of nitrogen for any given tank and its ullage volume. For example, consider the following:

Wing tank ullage at time of combat:

> 50 ft^3 volume
> wing temperature = + 10°F
> wing pressure = 1.5 psig
> altitude = 25,000 ft (pressure = 5.5 psia)

N_2 lost at post-combat refueling or N_2 required to fill the tank

$$PV = \frac{WRT}{M}$$

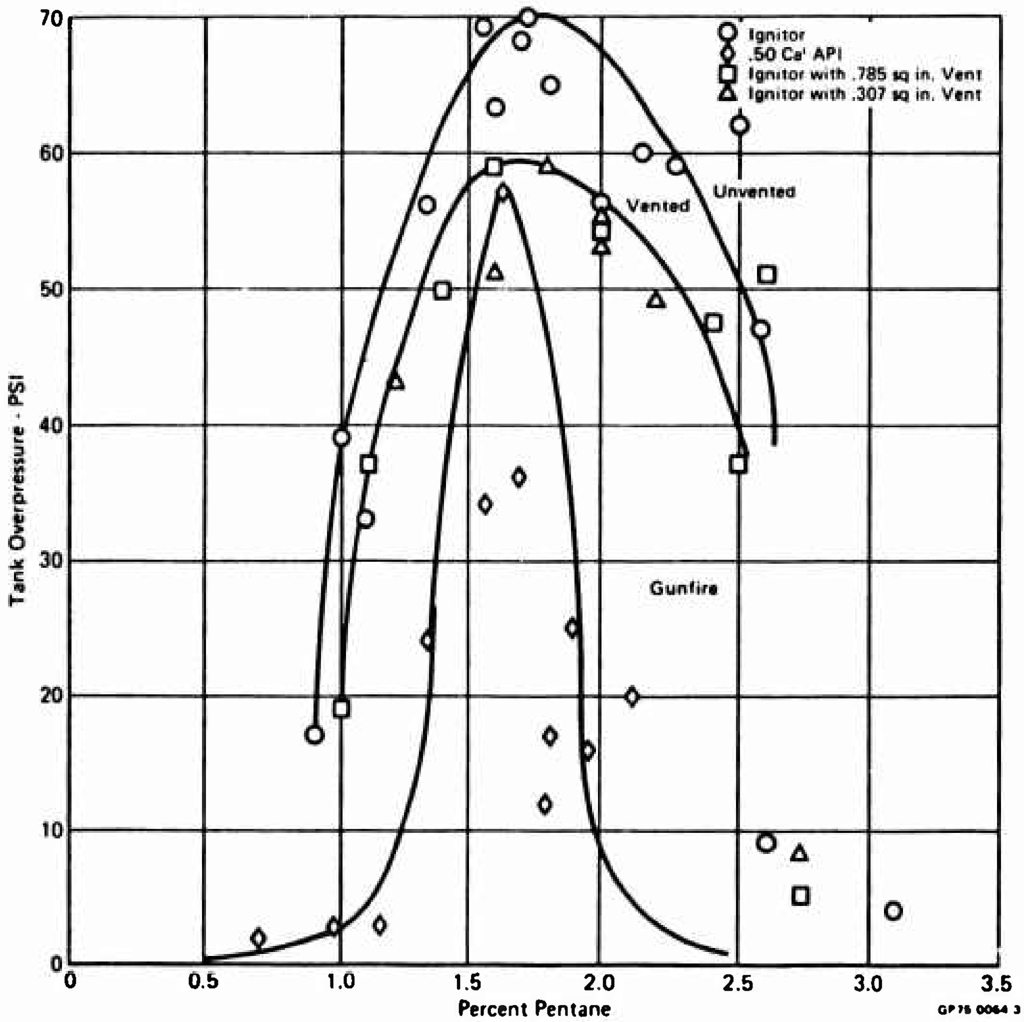

FIGURE 21
TANK OVERPRESSURE vs PERCENT PENTANE AT 12 ± 0.2% OXYGEN

$$W = \frac{PV\ (M)}{RT}$$

$$W = \frac{(5.5 + 1.5)\ (144)\ (50)\ (28)}{1544\ (460 + 10)}$$

$$W = 1.36 \text{ lb}$$

This procedure is followed for the total ullage volume in the aircraft after each combat excursion and totaled to determine nitrogen requirements. Several options are available to size the system. These include inerting all ullage throughout the entire flight, inerting only during combat and return flight, and inerting during combat only. The last, of course, is the lightest in weight for the aircraft in question. Scrubbing rates are figured using Stokes law relationships for bubble rise rate. The bubble size and composition are affected by:

1. The diffusion of nitrogen and oxygen into and out of the fuel
2. The diffusion of the fuel vapor into the bubble
3. Change of pressure with depth and tank total pressure
4. Rise time

By combining the nitrogen inerting and scrubbing volumes, the total inerting system may be developed and designed as shown in Figure 22.

The inflight scrubbing process may be discarded if the fuel transferred to the aircraft has been scrubbed and maintained under a nitrogen blanket, and if the aircraft fuel system vent is closed and pressurized by nitrogen during modes of the flight profile which would add air to the fuel. A non-venting closed-type system is also possible where the aircraft tanks are structurally capable of withstanding the pressure differentials with changes in altitude.

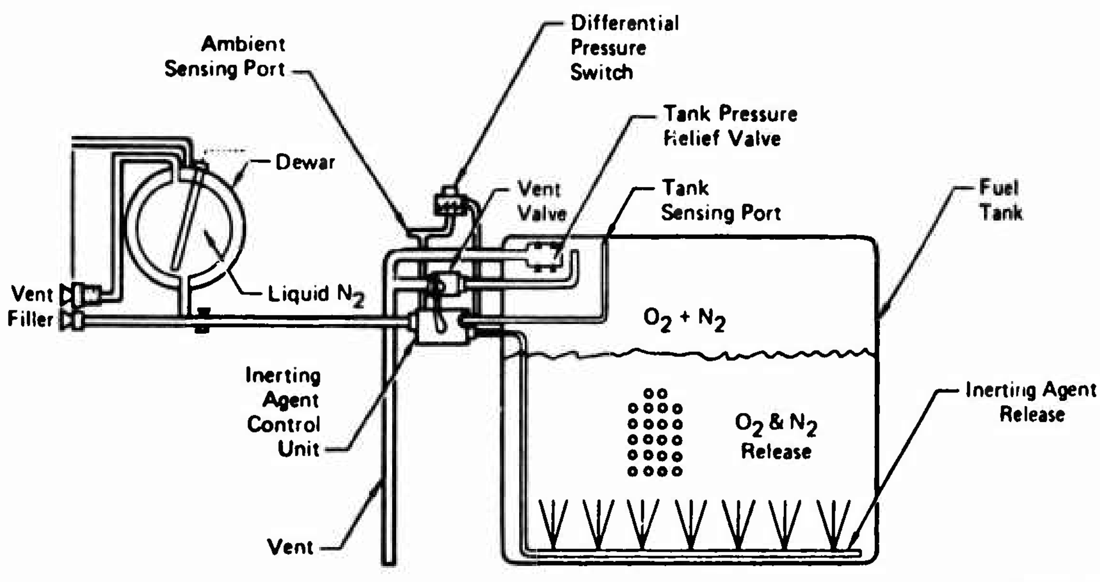

FIGURE 22
LN_2 DISTRIBUTION AND INERTING SCHEMATIC

	SYSTEM DESCRIPTION NARRATIVE CHART - NITROGEN INERTING
Principle of Operation	The nitrogen inerting system is a moderate weight active explosion-proofing mechanism that operates on the principle of oxygen dilution of the ullage and the fuel to a level below the concentration required to propagate a fire. It can be operated by using either a gaseous or a liquid nitrogen supply. The system requires a supply reservoir, pressure regulators, relief valves, and a pressure demand feed control, as well as, the necessary plumbing required for distribution to the fuel tank areas.
Application Constraints	The system must be designed to: (1) keep a slight positive pressure in the fuel tanks during the inerting cycle, (2) provide sufficient quantities of nitrogen for damage induced losses, (3) maintain the oxygen concentration level in the fuel tank ullage below that required to propagate a fire, and (4) be able to function in existing vent line and fuel tank arrangements and designs. Oxygen concentrations normally are not allowed to exceed 10 percent.
System Performance	Excellent fire and explosion protection as long as the fuel tank ullage oxygen concentration can be maintained at low levels. With large ignition sources, combustion will occur and overpressures will vary according to threat level, tank volume and oxygen concentration (Reference 22). Multi-hit capabilities are limited by leakage of nitrogen through battle damage.
Configuration	A generalized array of equipment required for the system is shown in the schematic, Figure 22. Automatic valving and sensing is required to compensate for changes in altitude.
Availability	All equipment required for this system is within the state-of-the-art and is readily available.
Additional Benefits	It can be used as a fire extinguisher in areas adjacent to the fuel tanks, such as dry bays and engine bays, but is not very efficient and would require additional plumbing and more nitrogen. The scrubbing action in the fuel by injecting small bubbles of nitrogen has, through limited testing, given indications of a reduction in hydraulic ram pressures.
Disadvantages	Logistics and maintenance requirements are high as facilities for supplying liquid nitrogen are required at each air base and regular periodic check of equipment is necessary to insure operation capability. It cannot be used in habitable compartments.

2.4.1.3 <u>Fuel Fogging</u> - The fuel-fog inerting system is based on two principles: first, that all aircraft fuels have a rich concentration limit of flammability; and secondly, that finely divided suspended liquid fuel (fog) acts, with respect to ignition and flame propagation, as if it were in the vapor state, (References 23 and 24). Since the rich limit is defined as the concentration of fuel vapor to air above which flame propagation cannot occur and fog acts as vapor, the addition of fuel fog to the tank ullage in sufficient quantity will theoretically cause the tank to be inert. The vapor concentration is dictated by the ambient total pressure and the fuel vapor pressure which is dependent on fuel temperature only. This being the case, the equilibrium flammability concentration of fuels is commonly expressed as temperature at any given altitude. The fog acting as a vapor adds to this vapor concentration lowering the fuel temperature required for the normal JP-4 rich flammability limit (Figure 23). It can be seen that a change in the rich limit of flammability occurs and is referred to as the degree of inerting. The inerting is measured by the depression down the temperature scale of this rich limit. These tests were performed using a spark ignition source of the capacitance-discharge type. With a change in ignition energy the rich limit, shift for JP-4, (Figure 24 and 25) indicating that the basic flammability boundaries are highly dependent on ignition energy. The degree of inerting from the fogging technique being used is approximately the same (34°F), regardless of the ignition energy; however, the total region is displaced. This indicates that there is a limit to the usefulness of a fogging system of this type with low volatility fuels where spray nozzles are used to produce simulated fog.

Hydraulic-type nozzles proved far superior to the pneumatic type nozzle, although both showed an ability to partially inert. Hydraulic-type nozzles operating at a pressure of 500 psig were able to suppress the rich flammable temperature limit of JP-4 a total of 35°F, while the pneumatic nozzles were able to suppress this limit by only 15°F. With very limited test data, the degree of inerting using the hydraulic nozzle was markedly improved (44°F depression) when the fuel supply was pressurized to 500 psig with nitrogen, and then fed into the nozzles. The inerting improvement established in these tests showed the system to be time-dependent, with time being the period that the fuel is fogged into the chamber. This same degree of improvement could possibly be realized with a pneumatic nozzle if the driving pneumatic supply were nitrogen.

The hydraulic nozzle that showed the best performance from a fog inerting standpoint is shown in Figure 26. This nozzle is operated by flowing high pressure fluid through a small hole (0.005 inch) in the exit face of the nozzle onto an impingement pin located directly in front of the exit hole. This impingement pin breaks up the fluid stream into small particles having an average diameter of 30 microns, which is well within the droplet size limitation of 10 to 100 microns required for droplet suspension (fog). Fog concentrations on the order of 0.14 lb of fuel per pound of air is needed to theoretically make the fuel ullage inert over the full operating range of temperature.

Additional evaluation of the fuel fog inerting concept was conducted in which the fuel was heated prior to fogging. This flashing of the fuel through the nozzle aperture provides further droplet break-up, resulting in a denser fog. Analysis of this test data indicated that a potential inerting capability existed when in a two nozzle system, one nozzle was fed warmer than ambient temperature fuel. Differences in fuel temperature as small as 5°F

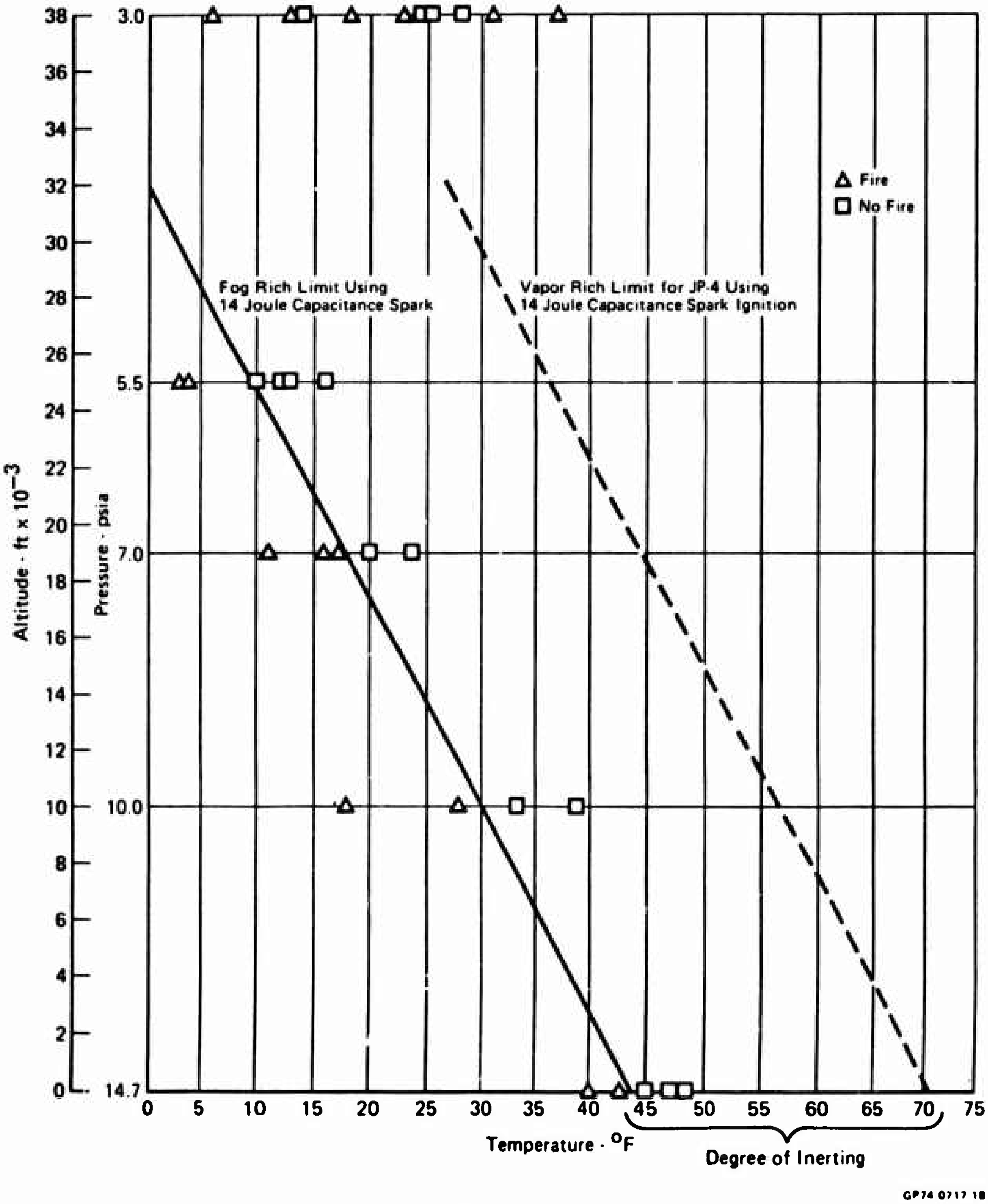

FIGURE 23
RICH LIMIT FOR JP-4 UNDER DYNAMIC FOG CONDITION

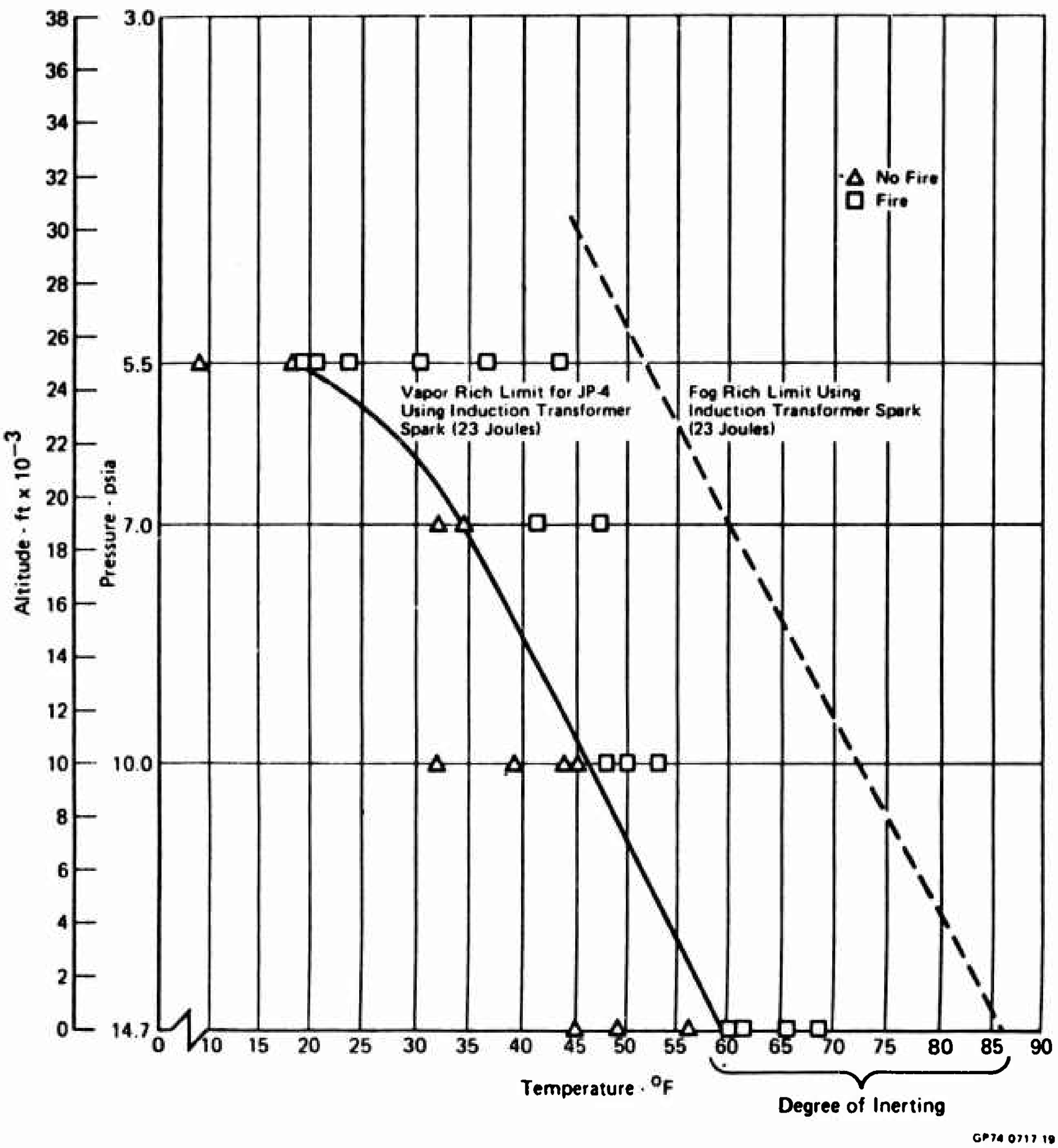

FIGURE 24
RICH LIMIT FOR JP-4 UNDER DYNAMIC FOG CONDITION USING 23 JOULE TRANSFORMER SPARK IGNITION SOURCE

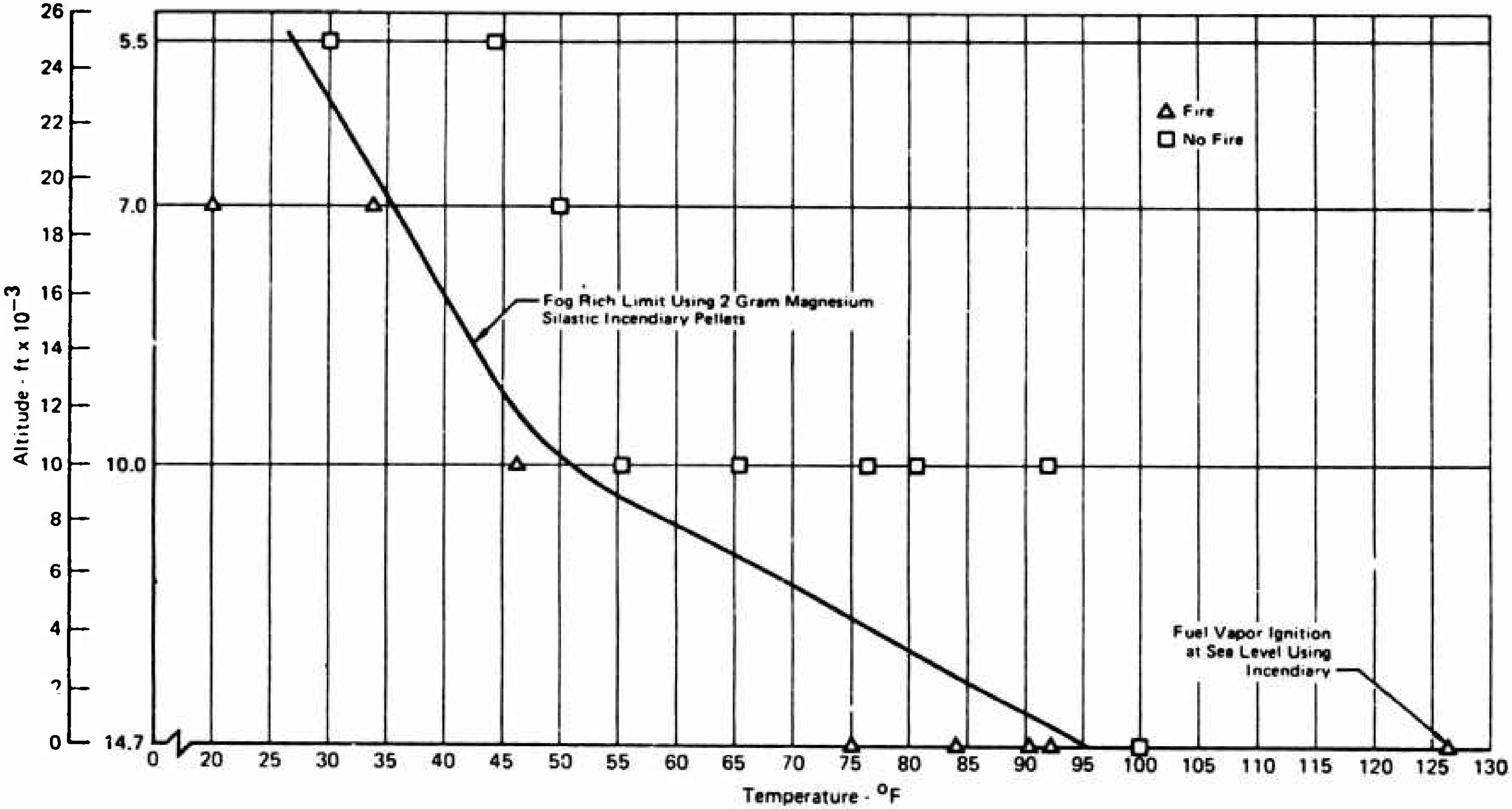

FIGURE 25
RICH LIMIT FOR JP-4 UNDER DYNAMIC FOG CONDITION
Incendiary Ignition Source

were tested. All the results of these tests pointed to inerting success when a match type ignition source was used. (Reference 23) Subsequent work (Reference 24) with fuel-burner-type nozzles showed that where 0.30 caliber incendiary projectiles were used for the ignition source, fire resulted in the ullage space each time. Two possible explanations are given for this: (1) the incendiary impact itself alters the ullage atmosphere, and (2) incendiary ignition does not depend on flame front propagation. Although only marginal inerting capabilities are possible at the present state of development of nozzles limited usage of this system is possible where the aircraft environment will permit this partial capability.

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FIGURE 26
HYDRAULIC IMPINGEMENT TYPE NOZZLE

SYSTEM DESCRIPTION NARRATIVE CHART - FUEL FOGGING

Principle of Operation	The fuel fog system is based on the principle that finely divided liquid fuel (fog) acts as it it were in the vapor state, adding to the natural vapor concentration; thereby driving the tank ullage to the over-rich condition.
Installation Constraints	A fuel fogging system lends itself well to either retro-fit or production installation. Plumbing requirements consist of tubing and nozzles to each tank, routed to provide the best ullage coverage with the fog spray. Fuel is used as the inerting medium, and the pressure required for the fuel nozzle flow may be provided by onboard pumps.
System Performance	System performance is dependent on equipment capable of creating and distributing very small (5 to 50 micron) fuel particles throughout the ullage of the tank. This is best done by spraying fuel at high (500 psig) pressure through nozzles designed to produce uniform fog dispersion. With state-of-the-art equipment, system performance is limited since only partial inerting with jet fuels is possible. This partial inerting is described best by reviewing Figure 23 and noting the depression in the rich flammability limit when a fuel fog is sprayed into the existing ullage of the tank. There is no known way to insure the system is always operating to required performance.
Configuration	The system configuration consists of nozzles, filters and the necessary plumbing to flow high pressure fuel to these nozzles. The fuel fog distribution manifold with fog nozzles must be located to produce uniform fog distribution through the fuel cells under all degrees of ullage and dynamic flight conditions.
Availability	Equipment as described herein is within the state-of-the-art, and is readily available.
Additional Benefits	This system offers the advantage of having minimum logistics support, no special handling techniques are required, and little if any maintenance is necessary.
Disadvantages	With present state-of-the-art hardware, fuel tank inerting over the entire flammability range of JP-4 is not realized. The system usage is thus limited to applications where the fuel temperature never gets more than 35°F below its rich limit. Work is continuing to improve the rich limit depression.

2.4.1.4 Extinguisher Type Explosion Suppression System - This type of explosion suppression system operates on the principle of detecting the initiation of a flame front and reacting to it by explosively dispersing a chemical extinguishing agent. The detector system is generally an infrared sensitive lead sulfide photo-electric cell which triggers an electric signal to initiate release of the extinguishing agent. Since photo-electric cells are line-of-sight-type detectors, complex or multicell fuel tanks require more than one detector and sometimes multiple dispensers. The detectors must also be shielded from all stray light to insure that the system is not inadvertently triggered. The chemical extinguishants used are quite efficient, requiring only 25 cc's per cubic foot of ullage protected.

Tests with this type of system using spark ignition have shown it to be very effective. However, gunfire ignitions using 0.50 caliber incendiary projectiles, have failed the system. The difference between the two ignition sources is time to peak pressure. With incendiary ignition this time ranges from 2 to 40 milliseconds while for spark ignition it can be 100 milliseconds or greater depending upon tank volume and other parameters. Decreasing the response time of the seeking and expelling system may overcome these combustion rates but the greater sensitivity would increase inadvertant functioning. Overpressures would still occur in spite of the reaction time because combustion will occur in the incendiary plume. This overpressure will be a function of the plume to ullage volume ratio and the available oxygen in the system.

The primary advantage of the system is its small volume.

The disadvantages are that is is a single-shot system although it lingers for a time dependent on vent rate, stray light from battle damage can deplete the extinguishant before it is needed, the complexity of the system degrades its reliability and maintainability, and finally, the dispenser containers are destroyed when the extinguishant is deployed increasing the logistics requirements.

	SYSTEM DESCRIPTION NARRATIVE CHART - FIRE EXTINGUISHING
Principle of Operation	The extinguisher type explosion suppression system is a light weight active technique operating by releasing an extinguishant into the fire zone once this fire is detected through its sensors. Halons 1301, 1211, 1011, 2402, and 1202 are the most commonly used extinguishants. Detectors are normally a light sensitive device installed in sufficient quantity to allow light detection at any location in the tank.
Application Constraints	This system must be installed so that complete coverage of the entire tank volume by the extinguishant is accomplished. In many aircraft tank designs, more than one bottle per tank is required. This same requirement is necessary in the case of the detector installation.
Configuration	The extinguishant system consists of a self-contained unit made up of the high pressure bottle(s) containing the extinguishing chemical and a detection device, usually a light seeking cell designed to trigger an explosive charge to disperse the agent from the bottle.
Availability	Equipment for this type system is readily available although improvements in detectors is required to make the system operational for high energy fuel-vapor ignition sources.
Additional Benefits	The required bottle installation is easily adaptable to any size and type fuel tank although more than one bottle per tank may be required.
Disadvantages	The fire extinguishing type system is not applicable where internal fuel tank peak combustion pressure is reached before the detector can activate the extinguishant as is the case for projectile induced ignitions. Logistics for this type system is high as after each activation the bottles must be replaced. Periodic inspection of the bottles is also required to insure that inadvertant activation has not occurred. A deactivation circuit is required for routine tank maintenance.

3.0 ADVANCED EXPLOSION PROTECTION TECHNIQUES

3.1 ON-BOARD NITROGEN GENERATING/INERTING SYSTEMS

The merits of nitrogen inerting explosion protection systems have been discussed in Section 2.4.1.2 of this report. The primary disadvantage of nitrogen inerting systems was identified as the logistic requirements, thus many schemes for generating inerting quality nitrogen on-board aircraft have been investigated. (References 26, 27, 28 & 29) Three candidate systems emerge; absorption, diffusion, and catalytic combustion systems. A description of each system follows along with a comparison summary.

3.1.1 Sorbent-Bed Inert Gas Generator

The sorbent-based fuel tank inerting concept is derived from the principle of oxygen absorption from air by a metal chelate, fluomine. The basic sorbent system consists of two beds; one absorbs oxygen from the air stream directed into the fuel tank ullage while the other simultaneously desorbs oxygen overboard. When the sorbent beds become fully loaded with (or depleted of) oxygen the air streams are reversed. Since absorption is carried out at higher pressures and lower temperatures than desorption and the heat of reaction must be removed or added during absorption/desorption respectively, these bed conditions must be cycled for system operation. A schematic of the system is shown in Figure 27. The system consists of a bootstrap compressor for air pressurization, heat exchangers for temperature conditioning, a freon heat of reaction transfer circuit and sundry switching valves for reversing flows and component functions. The valving complexity and number of rotating turbines, and complex functional controls result in a low reliability system compared to a liquid nitrogen storage system. The life of the chelate sorbent material is an unknown in this system in that it degrades during oxygen desorption, the degradation rate is a function of desorption temperature. The cyclic operation of the system makes the heat transfer complicated and has a questionable impact on its life size and weight. Reduced temperature oxygen stripping can be accomplished with low pressure air purging. Physical sorption bed such as molecular sieves are less temperature sensitive and could be used in lieu of chemical absorbants in a similar inert gas generator system. Unfortunately because of their co-absorption characteristics little or no separation occurs at equilibrium, however, dynamic separation does occur. Thus since their specific rates of absorption for oxygen versus nitrogen are significantly different a dynamic sorption system can be designed. A more complex system design results in that the oxygen concentration would be a function of flow rate pressure, temperature, and time.

3.1.2 Catalytic Reactor Inert Gas Generator

This system generates inert gas by reducing the oxygen concentration of bleed air through catalytic oxidation of jet fuel at low temperature. A constant mass flow of bleed air conditioned to 45 psig and 450°F along with fuel at stochiometric mix, feeds a reactor which is held at 1300°F. Excess inert gas flow is dumped overboard. Since constant mass flow

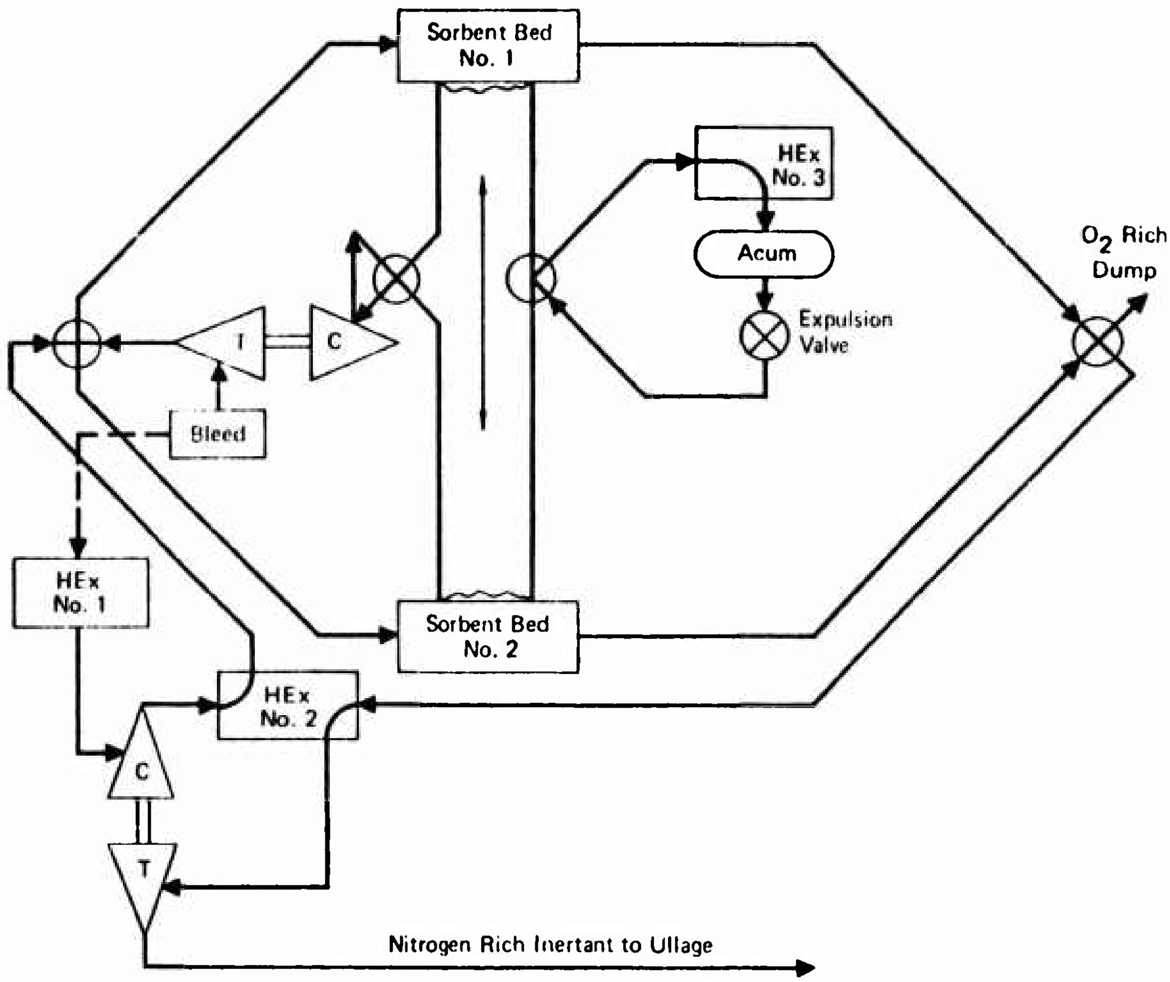

FIGURE 27
SORBENT-BASED INERTENT GENERATOR

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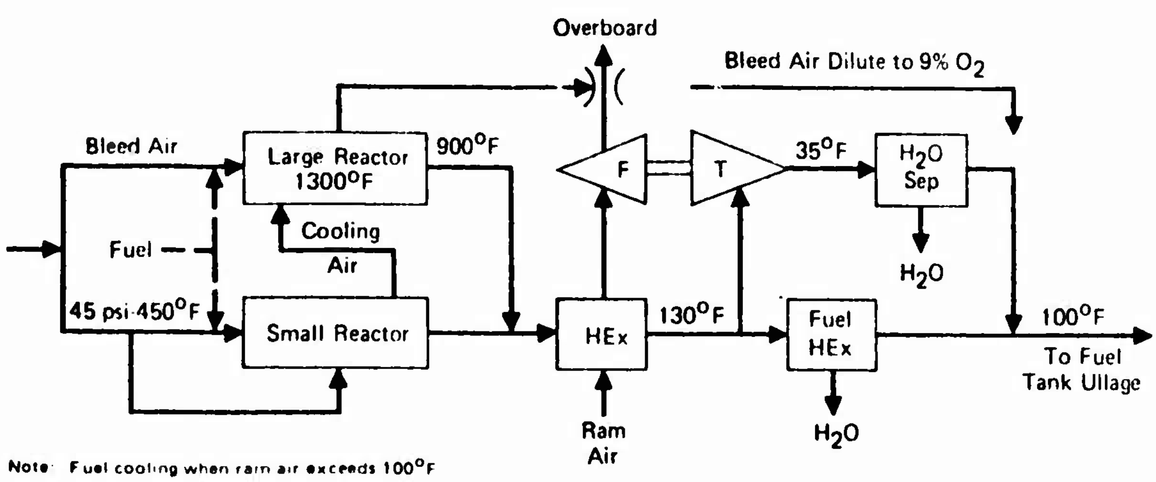

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FIGURE 28
CATALYTIC REACTOR INERT GAS GENERATOR

is a requirement for the reactor and the range of flows necessary for aircraft fuel tanks varies widely, the need for two reactors emerges to cut down on power waste. A small cruise reactor is included and advantage of this small unit is taken to simplify starting up and warm-up operations of the larger generator. The reactor and exiting inert gases are cooled with additional bleed air. Final cooling is accomplished with ram air cooling followed by turbine expansion. When ram air temperatures are too high, fuel cooling is substituted. Contaminant removal from the inert gases consists of manganese dioxide pellet removal of sulphur dioxide at the exit of the reactor, water removal by condensation and centrifugal separation, and particulate removal by final filtration. A schematic of the system is shown in Figure 28.

3.1.3 Permeable Membrane - Inert Gas Generator

The permeable membrane inert gas generator system works on the principle of selective gas diffusion where oxygen is preferentially removed from the primary gas stream. The membranes are made of organic polymeric materials which transfer oxygen more readily than nitrogen with mass transfer ratios on the order of 4:1. Organic, ceramic, and metallic materials are available but the selection of membrane material is a compromise based on physical properties and mass transfer rates as well as separation efficiency. The mass transfer rate relationship of each gas species through the membrane is given by the following equation.

$$Q = \frac{SD(\Delta P)A}{t}$$

Q = mass transfer rate
S = solubility coefficient
D = diffusion coefficient
P = species partial pressure differential
A = transfer area
t = membrane thickness

From the equation it is quite apparent that both solution and diffusion are combined in the process and the product of their coefficients is the permeation coefficient. Thus the mass transfer mechanism starts by the solution of the gas species into the membrane setting up a concentration gradient across the membrane which drives the diffusion. Dissolution of the gas species on the opposite surfaces maintains the concentration gradient and mass flow. Although gas diffusion is only part of the transfer mechanism it is usually rate controlling allowing the surface concentrations to reach near equilibrium with the gas streams partial pressures in accordance with Henry's law. In order to limit the weight and volume of the permeation unit, the area must be minimized which means partial pressure differential to thickness must be optimized to the maximum. The ultra thin hollow micro fiber technology approach makes the permeable inert gas generator system practical. Figure 29 is a schematic of such a system. The system uses bleed air as the primary stream. A turbine/compressor, heat exchanger, water, and dust separators precondition the air prior to processing. Ram air is used for cooling as well as sweeping the oxygen rich fraction overboard. During ground operation fan air replaces ram air requiring auxiliary power.

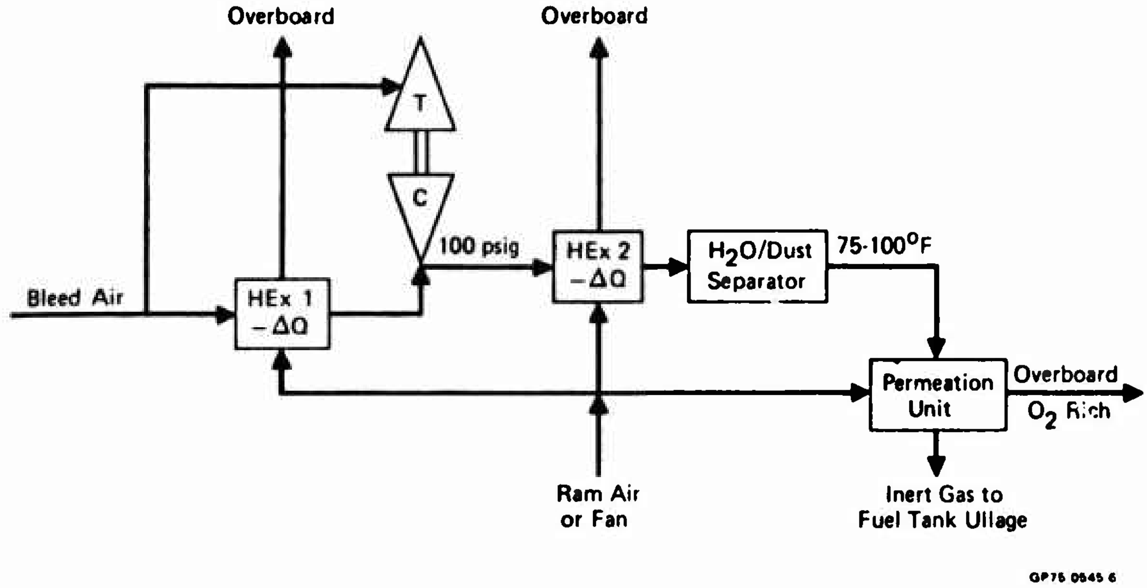

FIGURE 29
PERMEABLE MEMBRANE INERT GAS GENERATOR

3.2 COMBINATION SYSTEMS

The capability of foam, fuel fog, and nitrogen inerting in protecting aircraft fuel tanks from damaging projectile-induced explosions has been demonstrated. However, these systems have limiting characteristics which restrict their overall usage. For instance, foam explosion-suppression systems, while passive and logistics-free, exhibit higher weight and displacement penalties for single-cell, low-structural-strength fuel tanks. Fuel fog is an active logistics-free system, but has limited inerting effectiveness, particularly for low-volatility fuels and cold ambient temperatures. Nitrogen inerting, because it is an active system, has decreased reliability and requires increased logistics. Its weight penalties, however, are quite low and it is insensitive to scaling. Preliminary test data obtained to date indicates that improved system performance and a reduction in weight and logistics penalties could be achieved by combining the best characteristics of each system. The candidate systems considered include:

3.2.1 Gross Voided Foam Diluent Systems

The gross voided foam system trades off weight for combustion pressure rise to the extent that can be withstood structurally by the tank. The combination of this system with partial nitrogen inerting appears to have merit in that the maximum overpressure is significantly reduced, with the addition of small amounts of nitrogen. Thus, the attenuating effects of the voided foam will result in much lower tank overpressures, or at the same overpressure, greatly reduced foam requirements. The reduced nitrogen requirement could make on-board nitrogen generator systems viable, and the combined system could be attractive from the standpoint of weight, displacement and logistics over a pure nitrogen inerting system. Other inert gases or halogenated hydrocarbons may be even more effective.

3.2.2 Fuel Fog Diluent Systems

Fuel fogging works on the principle of producing an over-rich non-flammable ullage. The fog and the fuel vapor are additive, thus making the fuel-to-air ratio higher at low temperatures, which in turn depresses the temperature at which inert conditions exist. Past work with fuel fogging has shown that the fog concentration is limited, and without the contribution of sufficient fuel vapor, the ullage is explosive. The addition of inertants, such as nitrogen and Halons, severely depresses the rich limit and thus may reduce the fog concentration required at any given temperature to establish over-rich inert conditions, as shown in Figure 30.

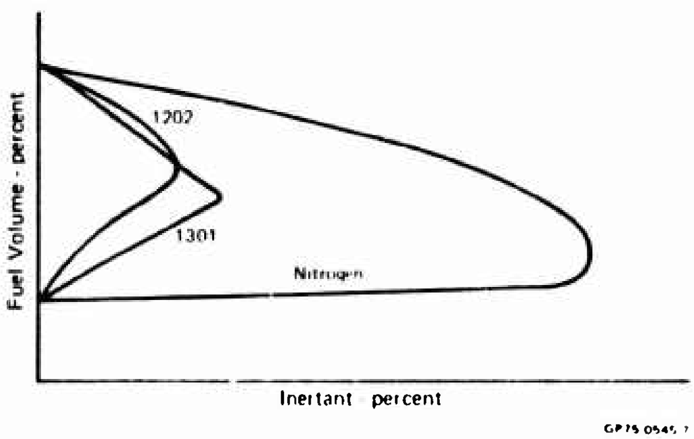

FIGURE 30
JP-4 VAPOR INERTING

One complicating factor revealed in previous fuel-fog-inerting investigations is that the rich limit is a function of ignition energy. Higher ignition energies extend the rich flammability limit. The addition of an inert gas, however, can eliminate or attenuate flame propagation, and thus reduce the maximum combustion overpressure generated.

3.2.3 Anti-Mist Additive Systems

The conclusions from recent tests involving the addition of anti-misting compounds to commercial grade aviation fuel, indicated a significant potential reduction in crash type fuel fires (Reference 30). Subsequent work involving 0.50 caliber API gunfire ignition tests also reached similar conclusions. The results of these tests, showing potential additives and their respective combustion overpressures, are presented in Figure 31. It can be seen that the anti-misting additives were effective only with low volatility fuels (for example, JP-8) and their effectiveness was essentially negated with higher volatility fuels such as JP-4 (Reference 31). Caution must be exercised, however, in making this observation, because of the fuel temperature conditioning. The ambient temperature (60-70°F) test conditions placed JP-4 well within its flammability range, whereas JP-8, the lower volatility fuel, is in the very lean condition. Since fuel droplet number and size has considerably less effect on the vapor in the flammability range, the anti-misting compound will therefore have a negligable effect on the flammability of JP-4 using these temperature ranges. Further investigation of the various additives and the mechanism involved in their operation is warrented where the fuels tested are temperature conditioned to their respective flammability ranges. Once the mechanism of how the additive actually operates is learned, additional materials might then be developed that would greatly extend their effective range.

Fuel/Additive*	Total Shots	No. of Reactions	Average Pressure Rise (psi)	Highest Pressure (psi)	No. of Reactions Over 10 psi**
Base Line Neat JP-4	16	14	54.8	72.0	14
Neat JP-8 (Flash Point 114°)	15	13	38.0	55.0	13
JP-4 + FM-4	15	12	67.5	79.0	12
JP-8 + ESSO A	16	16	31.7	62.0	14
JP-8 + FM-4	16	14	8.6	40.0	2
JP-8 + AM-1	15	12	9.8	33.0	3
JP-8 + XD 8132	15	15	13.1	30.0	6

* All fuel additives at a concentration of 0.3% by weight with exception of XD 8132. Concentration was 0.7%.

** 10 psi is considered within the structural limits of most aircraft fuel tanks and is acceptable from a system success standpoint.

FIGURE 31
SUMMARY OF ANTI-MIST FUEL ADDITIVE EVALUATION

4.0 ADVANCED EXPLOSION PROTECTION TECHNIQUES - COMBINATION SYSTEM TEST PROGRAM

4.1 INTRODUCTION

The capability of foam, fuel fog, and nitrogen inerting systems to protect aircraft fuel tanks from damaging projectile-induced explosions has been demonstrated. All these systems, however, have some limiting characteristics which restrict their usage. Foam explosion-suppression systems, while passive and having low maintenance and logistics, exhibit higher weight and displacement penalties for single-cell low-structural-strength fuel tanks. Fuel fog which is an active relatively low logistic support and maintenance system, has limited inerting effectiveness, particularly for low-volatility fuels and under cold conditions. Nitrogen inerting which is also an active system, has low reliability and also requires increased logistics. The weight penalty for the nitrogen system, on the other hand, is relatively low and is insensitive to scaling, however altitude excursions increase the N_2 demand and the fuel tank vent system must be closed. In reviewing these inerting systems, it was conjectured that combining the best characteristics of each could lead to an improved performance system with reduced weight and logistic support penalties. Exploration of this possibility, therefore, formed the objective of this portion of the program.

The investigation itself consisted primarily of exploring the effects of adding nitrogen in combination with varying void percentages of reticulated foam, and fuel (JP-4)/air fogs. In both cases, baselines were first established using propane/air mixture with varying percentages of nitrogen and fuel/air fog at varying temperatures. Additional background information, such as the energy required to ignite various percentages of nitrogen diluted fuel/air fog mixtures at various temperatures, was also determined.

4.2 TEST SETUPS AND PROCEDURES

All testing was performed in a 12.5-inch diameter by 21.5-inch long cylindrical test chamber, shown in Figure 31. This 1.5 cubic foot chamber was equipped with a 1-inch thick lucite lid used in the nitrogen/foam tests and an aluminum lid for the fuel/air fog tests.

4.2.1 Nitrogen Dilution of Propane/Air and Propane/Air/Foam

The test schematic for the nitrogen dilution of the propane/air and propane/air/foam combinations is shown in Figure 32. Two different types of reticulated foam were used in the tests, the majority of which were run using the 25 pores/inch red foam. Some baseline and 70% void tests were also run with 20 pores/inch blue foam. For expediency, the baseline tests (without foam) were performed concurrently with the foam tests through the use of the in-line sampling bomb. The latter could be isolated from the test chamber after each had been filled with the selected gas mixture and then independently ignited to obtain the baseline data. Foam was initially applied to the vertical wall of the test chamber, however, because of the small chamber volume, the foam thickness for an 80% void was of marginal effectiveness and prohibited the testing of a 90% void configuration. This test setup was subsequently modified by relocating the foam immediately below the lid, thereby permitting increased foam thickness for each void percentage.

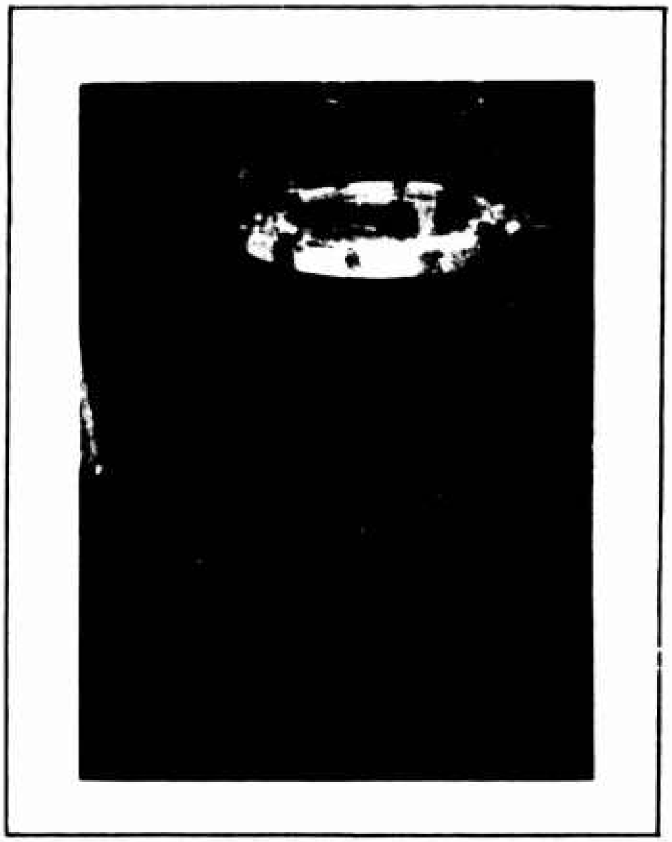

FIGURE 32
12 IN. DIAMETER TEST CHAMBER

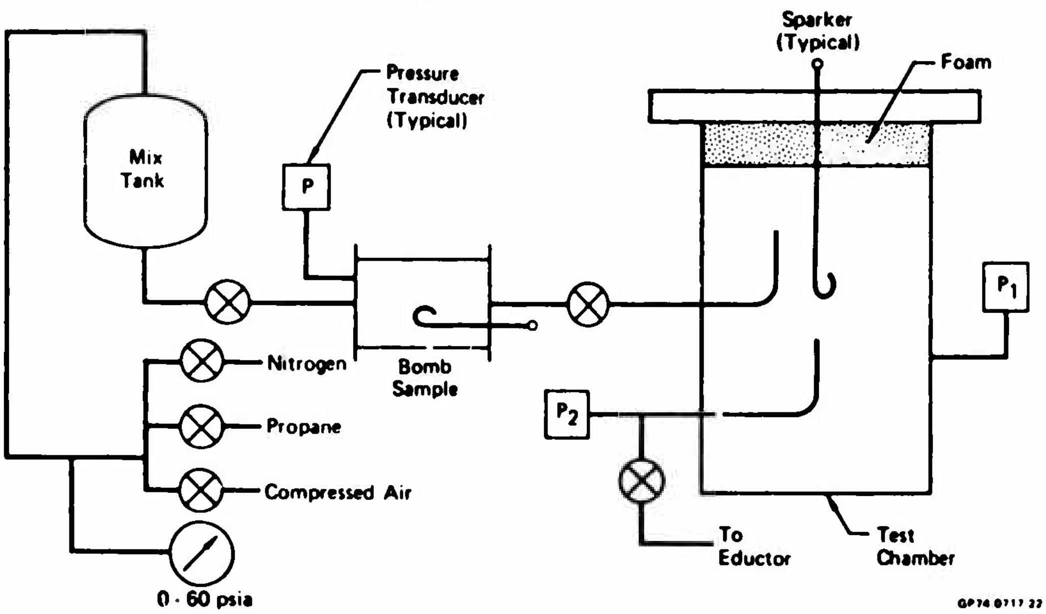

FIGURE 33
TEST SCHEMATIC FOR NITROGEN DILUTION OF PROPANE/AIR AND PROPANE/AIR/FOAM COMBINATIONS

An initial test procedure adopted by the test laboratory was later changed after it was discovered that the propane concentration was constant. As a result of this problem, the test engineer was directed to use the following formula for correctly determining the percentage of constituent gases in all the subsequent tests:

$$\frac{\text{Propane (Commerical Grade)}}{\text{Total Gases - (Nitrogen + Propane)}} = .06$$

The detailed test procedure finally used was as follows:

(a) Wet the selected piece of foam in JP-5, allow to drain for one minute and install in the test chamber.

(b) Bolt down lid of test chamber

(c) Evacuate the test chamber, bomb sampler and mix tank to 0.3 psia.

(d) Isolate the bomb and test chamber from the mix tank.

(e) Bleed air back into mix chamber to 1 psia.

(f) Add propane (partial pressure) to appropriate gage reading (corrected for ambient pressure).

(g) Add balance of air to required gage reading, based on partial pressure of the gas.

(h) Add selected amount of nitrogen to required gage reading.

(i) Bleed gas mix through the bomb and into the test chamber until the system pressure is equalized.

(j) Isolate the mix chamber, open outlet valve on test chamber and bleed bomb and test chamber down to ambient pressure.

(k) Close outlet valve and isolate bomb and test chamber.

(l) Ignite gas mixture in bomb and record the results.

(m) Ignite gas mixture in the test chamber and record the results.

4.2.2 Nitrogen Dilution of Fuel/Air Fog

The test schematic for the fuel/air fog and the nitrogen dilution of the fuel/air fog is shown in Figure 33. A sonic type pneumatic nozzle was used to produce the fogs, which consisted of droplets of approximately 5 to 50 micron diameter. The basic test procedure used consisted in spraying the JP-4 fuel through the nozzle for a five minute period prior to ignition, in order to stabilize the temperature conditions. The test chamber was vented to the atmosphere during this period to maintain the ambient pressure conditions. The lid of the test chamber was permanently raised off the sealing face of the chamber body by spacers for the majority of the tests. This vent area was then closed off with masking tape

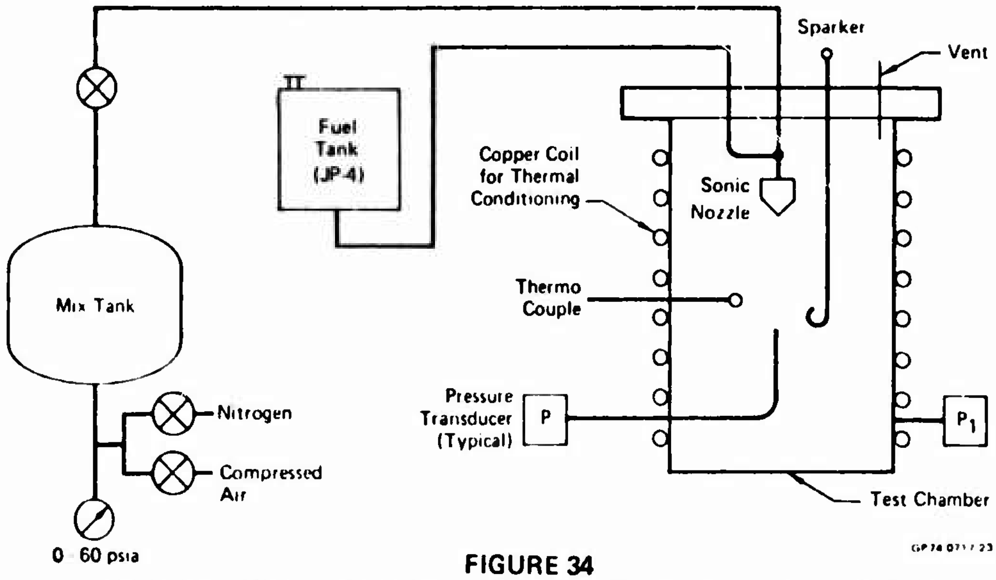

FIGURE 34
TEST SCHEMATIC FOR FUEL/AIR FOG AND NITROGEN DILUTED FUEL/AIR FOGS

prior to each test. This technique was performed after one of the first fuel/air tests shattered the original lucite lid. The lid was fully seated, however, during the last series of tests in which peak pressures had to be measured.

Ignition energy levels for the nitrogen diluted fuel/air fogs was initially determined using a 25 millijoule capacitance discharge sparker. This was later replaced by a rheostat controlled 110 volt spark ignition system when the former proved to be inadequate.

The detailed test procedure used for the ignition energy level study was as follows:

(a) Pressurize the fuel storage tank to 7 psig using compressed air.

(b) Mix a bottle of compressed air and nitrogen varying the percentage of nitrogen. A new mix was made each time the percentage of nitrogen was changed.

(c) Set the compressed gas regulator to 10 psig flow pressure.

(d) Open the fuel metering valve two turns to establish a fuel fog in the tank.

(e) Let the flow continue for 5 minutes allowing the tank to vent.

(f) Install the sparker and connect this electrical cables.

(g) Set the sparker power controls to 20%, start the oscillograph at 4 inches/second. Press the sparker switch. If there is no ignition increase the controller in increments of 5% until ignition or 60% point is reached.

(h) Close the fuel metering valve and turn off the gas supply.

4.3 TEST RESULTS

4.3.1 Nitrogen Dilution of Propane/Air and Propane/Air Foam

Combustion overpressure data was obtained for a stoichiometric propane/air mixture at 26, 50, 70, 80, and 90 void percents for red foam (25 ppi), and nitrogen dilutions of 0, 5, 9.1, 16.67, 23.08, 28.57, 32.89 and 35 percent respectively. These data are plotted in Figure 34. In addition, overpressures were also measured for nitrogen dilutions of 0, 5, 10, 15, 20, 25, 30, 35, and 40 percent with blue foam (20 ppi) at 70 void percent.

4.3.2 Nitrogen Dilution of Fuel/Air Fog

Ignition energy values were obtained for neat fuel/air fog over the temperature range of 30° to 70°F. Values for 20 and 30 percent nitrogen dilutions were also obtained over a temperature range of 15° to 100°F. These data are reported in Figure 35 and plotted in Figure 36. In addition, overpressures were also measured for fuel/air fogs with 10, 20, and 30 percent nitrogen respectively, over a temperature range of 20° to 60°F. These data plotted as pressure (peak, psia/ambient) versus temperature are shown in Figure 37.

4.4 CONCLUSION

4.4.1 Nitrogen Dilution of Propane/Air Foam

From the data generated to date, two conclusions can be drawn. First, foam/nitrogen explosion suppression is more effective at foam voids greater than 50 percent for single-cell configurations, and second, greater reductions in combustion overpressure are derived from the initial 20 percent of nitrogen. Analysis of the data reveals another interesting point, namely, that the combustion overpressure is reduced by a factor of approximately two. This would indicate that by the addition of only small amounts of nitrogen to a voided foam system, the amount of foam required to maintain an equal combustion overpressure could be effectively reduced.

4.4.2 Nitrogen Dilution of Fuel/Air Fog

While the addition of increasing amounts of nitrogen to the fuel/air fog reduces the ignitability of the resulting fog, the ignition energy values appear to approach one another at about the stiochiometric temperature of the JP-4 vapor.

A review of the data generated further shows that addition of nitrogen to pneumatically generated fuel/air fogs provide some reduction in overpressure. This reduction, however, is not proportional to that obtained in a nitrogen inerting system without fog. The fog, in other words, appears to defeat the effect of nitrogen inerting at least for the pneumatically generated fogs. As an example, the baseline curve (no foam), shown in Figure 34, indicates a pressure ratio (P_2/P_1) of 5.75 at 30 percent nitrogen, whereas an equal amount of nitrogen to the fuel/air fog (Figure 37) shows a pressure ratio of 7.3.

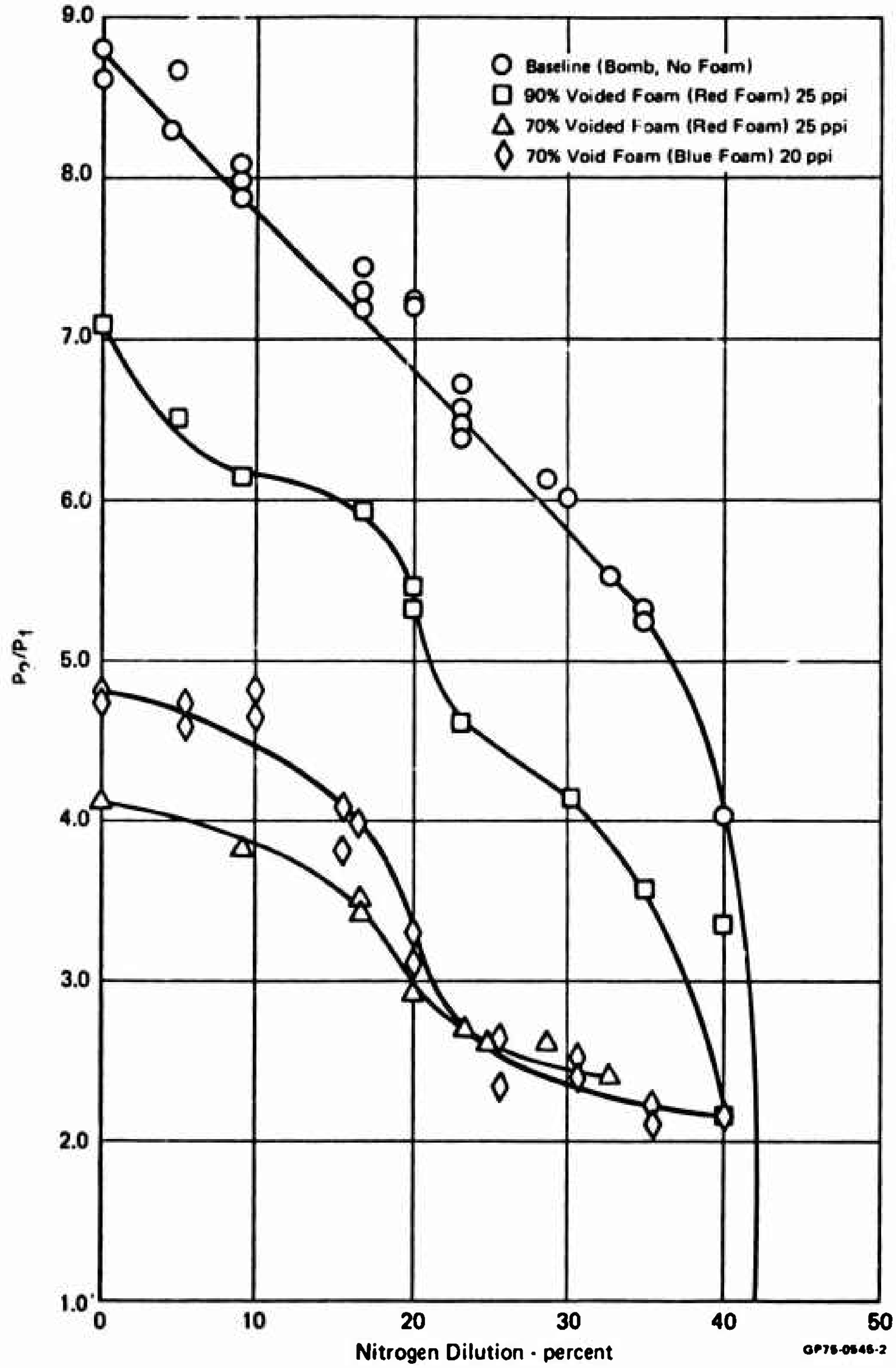

FIGURE 35
NITROGEN DILUTION WITH AND WITHOUT FOAM

Test No.	Fog Temp (°F)	Powerstat Setting	Ambient Temp (°F)	Flow Time (min)	Fire No Fire	Energy (Joules)
0% N_2 Added						
1	72	25	66	5.0	No Fire	1.05
2	72	40	66	7.0	Fire	1.65
3	74	25	66	10.0	Fire	1.05
4	75	25	66	5.0	Fire	1.05
5	67	15	73	5.0	Fire	0.63
6	78	15	71	5.0	No Fire	0.63
7	78	20	71	7.0	Fire	0.84
20% N_2 Added						
1	74	15	75	5.0	No Fire	0.63
2	74	18	75	6.0	No Fire	0.75
3	74	20	75	6.5	Fire	0.84
4	87	25	78	6.0	No Fire	1.05
5	87	28	78	8.0	Fire	1.17
6	70	18		5.0	No Fire	0.75
7	70	20		5.0	Fire	0.84
8	55	25		5.0	No Fire	1.05
9	55	28		5.0	Fire	1.17
10	72	20	70	5.0	No Fire	0.84
11	72	23	70	5.0	Fire	0.96
12	84	25	70	5.0	No Fire	1.05
13	84	28	70	5.0	Fire	1.17
14	90	28	70	5.0	No Fire	1.17
15	90	30	70	5.0	Fire	1.26
16	60	15	70	5.0	No Fire	0.63
17	60	18	70	5.0	Fire	0.75
18	45				No Fire	
19	54	20	70	5.0	Fire	0.84
20	56	15	70	5.0	No Fire	0.63
21	56	16	70	5.0	Fire	0.675
22	55	15	55	8.0	No Fire	0.63
23	55	18	55	8.0	Fire	0.75
24*	66	18	55	5.0	No Fire	0.75
25	66	20	55	5.0	Fire	0.84
26	45	15		5.0	No Fire	0.63
27	45	18		5.0	Fire	0.75
28	42	17		5.0	No Fire	0.72
29	42	18		5.0	Fire	0.75

Test No.	Fog Temp (°F)	Powerstat Setting	Ambient Temp (°F)	Flow Time (min)	Fire No Fire	Energy (Joules)
20% N_2 Added (Continued)						
30	45	15		5.0	No Fire	0.63
31	45	16		5.0	Fire	0.675
32	57	15		5.0	Fire	0.63
33	65	15		5.0	No Fire	0.63
34	65	16		5.0	Fire	0.675
35	25	100		5.0	No Fire	3.6
36	36	100		5.0	No Fire	3.6
37	45	35		5.0	No Fire	1.47
38	45	40		5.0	Fire	1.65
39	50	15		5.0	No Fire	0.63
40	50	18		5.0	Fire	0.75
41	53	18		5.0	No Fire	0.75
42	53	19		5.0	Fire	
30% N_2 Added						
1	87	25	78	6.0	No Fire	1.05
2	87	28	78	8.0	Fire	1.17
3	70	20	78	6.0	No Fire	0.84
4	70	23	78	6.5	Fire	0.96
5	50	25	72	5.0	No Fire	1.05
6	50	28	72	5.0	Fire	1.17
7	62	23	72	5.0	No Fire	0.96
8	62	25	72	5.0	Fire	1.05
9	74	100	72	5.0	No Fire	3.6
10	84	100	72	5.0	No Fire	3.6
11**	70	35	73	5.0	No Fire	1.47
12	70	40	73	5.0	Fire	1.65
13	75	50	73	5.0	No Fire	
14	56	15	73	5.0	Fire	0.63
15	58	23	73	5.0	No Fire	0.96
16	58	25	73	5.0	Fire	1.05
17	65	18	73	5.0	No Fire	0.75
18	65	20	13	5.0	Fire	0.84
19	70	40	73	5.0	No Fire	1.65
20	70	43	73	5.0	Fire	1.80
21	46	18	73	5.0	No Fire	0.75
22	46	20	73	5.0	Fire	0.84
23	36	20	73	5.0	No Fire	0.84
24	36	23	73	5.0	Fire	0.96

Notes

*Plot points 24 thru 36

**Same bottle of mixed air/N_2 used for tests 11 thru 24

FIGURE 36
FUEL FOGGING

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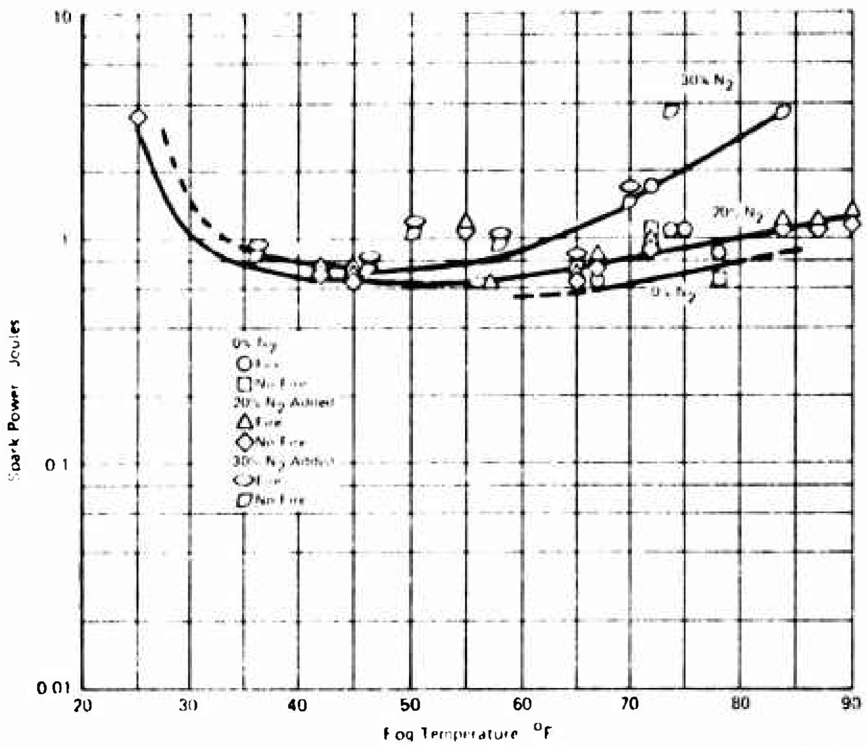

FIGURE 37
FUEL FOG IGNITION TESTS

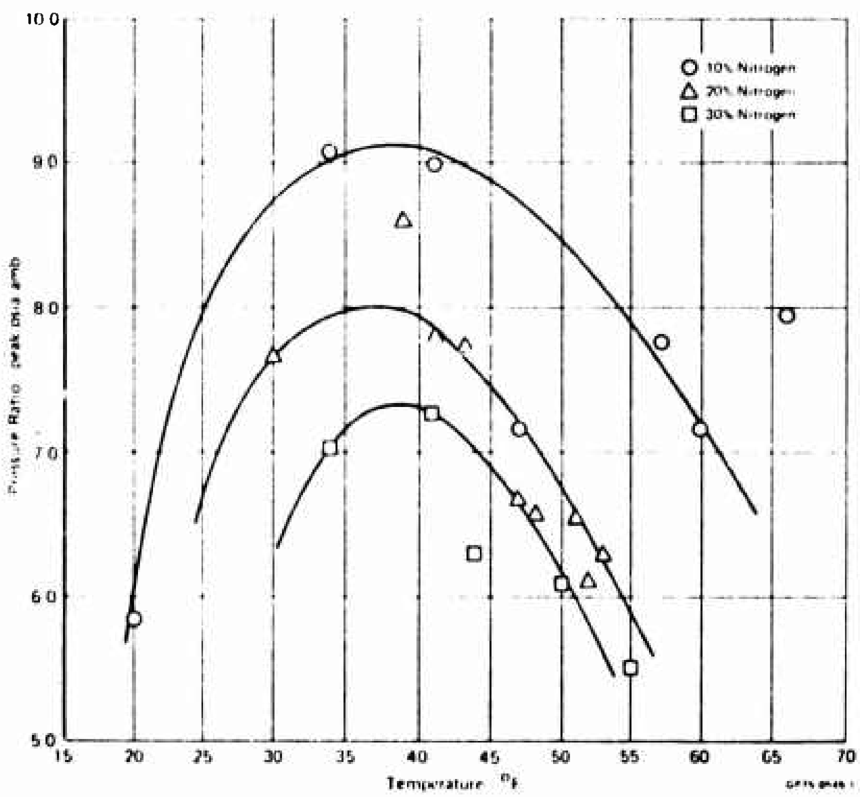

FIGURE 38
FUEL FOG TESTS WITH NITROGEN DILUTION

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